LABORATORY STUDY OF PLUNGING BREAKER WAVE FORCE DISTRIBUTION ON A SLENDER PILE

An Engineering Report

by

HAROLD JEROME REDDISH

LABORATORY STUDY OF PLUNGING BREAKER WAVE FORCE DISTRIBUTION ON A SLENDER PILE

An Engineering Report

by

HAROLD JEROME REDDISH

Submitted to the Faculty of
the College of Engineering
Texas A&M University

in partial fulfillment of the requirement for the degree of

MASTER OF ENGINEERING

Major Subject: Ocean Engineering

ABSTRACT

The dvnamic nature of breaking wave forces on structures in the surf zone are considerable. Design of a structure not taking these forces into account can cause both damage to the structure and possibly loss of life. Past studies by previous investigators have contributed considerable knowledge about the makeup and character of breaking wave forces impacting on vertical walled structures, but little study has been devoted to the dvnamics of breaking wave forces on a pile.

An attempt to develop and test a device which would be of benefit in measuring breaking wave forces was undertaken. An experimental device consisting of several strain gauges positioned inside a small cylindrical, hollow pile section was tested and the results analyzed. Good agreement between this study and results of similar experiments was obtained.

This report reviews past and current efforts of investigators studying breaking wave forces on a pile, describes the design and analysis of an experimental wave force measuring device, and presents data collected from actual laboratory studies carried out with the experimental wave force measuring device. This study was performed in the glass walled wave channel in the Hydromechanics Laboratory of Texas A&M University.

ACKNOWLEDGEMENT

The author is deeply indebted to Dr. David R. Basco, for his contagious enthusiasm, active participation and guidance in this effort. Appreciation is also expressed to Dr. John M. Niedzwecki and Dr. Stan J. Miley, for their advice and participation as members on my committee.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

NOMENCLATURE

A	=	Projected area of object perpendicular to the velocity
Cb	=	Breaking wave celerity
Cd	=	Coefficient of drag
Cm	=	Coefficient of mass
d	=	Depth of still water
Dt	=	Thickness of entrapped air between wave face and wall
D	=	Pile diameter
H	=	Wave height
Hb	=	Height of breaking
L	=	Wave length
K	=	Length of water column
kb	=	Wave number
Nc	=	Crest height above still water level
Pi	=	Pressure
Pmax	=	Maximum pressure
S	=	Distance above bottom
t'	=	Width of pressure transducer
T	=	Wave period
Tzdb	=	Zero-Downcross wave period at breaking
U	=	Velocity of water
w	=	Specific weight of water
Vm	=	Volume of displaced fluid
ρ	=	Mass density of water
λ	=	Curling factor
Ω	=	Dimensionless pressure

CHAPTER 1

INTRODUCTION

Breaking waves and their associated forces on coastal structures and facilities pose a challenging and difficult problem for todays ocean engineer. With the continued dynamic growth and development of our coastal zones, ocean engineers are faced with new design concepts and constantly pushed to expand and refine currently accepted methods of design and construction.

Over the past 150 years steady progress has been made in the descriptive and analytical explanation of ocean wave phenomena. Men such as Stokes and Airy developed mathematical theories which were used by early engineers for design purposes, and sparked interest in the study of ocean waves. Man continued to improve and expand upon his knowledge of deep and shallow water waves but has fallen short in adequately describing the complex, non-linear surf zone home of the breaking wave.

It has been just recently that man has actively pursued a thorough understanding of breaking waves, their characteristics, forces, and tried to mathematically describe the physical process of these waves. Concerted efforts have been expended to describe the force of breaking waves on vertical walls, breakwater structures, pile configurations and platforms. Each yielded a little more insight into the overall picture of the breaking wave story.

The use of an equation developed by Morison, Johnson and O'Brien (1953), has been proven to adequately predict forces on a pile exposed to surface waves of a given height and period.

Unfortunately this equation does not remain valid in the prediction of breaking wave forces. It has been discovered by several investigators that when a wave breaks on a pile there exists two distinct forces. One is a large, sudden, short duration force commonly referred to as an impact force or shock force and the other a longer duration, smaller in magnitude force called a secondary force or oscillatory force. The impact force of a breaking wave is considerable and is a major factor to be considered in the design of coastal structures for the magnitude of this force is several times that of those predicted by Morison's equation.

This report has focused on one aspect of breaking wave phenomena. Specifically, trying to record the force exerted on an experimental force measuring device by a plunging breaker. Two goals were to be achieved:

1. The design and development of a force measuring device capable of measuring the impact and oscillatory forces of plunging breakers in a laboratory wave tank.
2. The use of this instrument to capture, record and evaluate the vertical distribution of plunging breaker forces.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical

The study of breaking wave forces has been of interest for many years. Varied interest has ranged in the study of these forces on many different type structures, such as piles, vertical walls, breakwaters and other coastal structures.

Gaillard (1904), of the U.S. Army Corps of Engineers was an early pioneer who developed a spring dynamometer to measure the pressure of breaking waves against seawalls and breakwaters situated in the Great Lakes. Although his measuring equipment was not sensitive to impact pressures developed by breaking waves he was able to obtain reasonable measurements of what is commonly called today the secondary or oscillatory pressure of breaking waves.

Larras (1937), conducted the first laboratory study in France of breaking waves on a vertical wall. His experiment documented the presence of a very rapid pressure rise followed by a secondary pressure of longer duration. Larras was unable to explain the short duration rise in pressure and presented no numerical data of this phenomena.

Other investigators were becoming very interested in the discovery of this rapid rise shock pressure and launched several field and laboratory experiments to investigate Larras's findings. In 1938 a field study by De Rouville, Besson, and Petry (1938), confirmed the finding of Lauras as to the existence of a rapid rise shock pressure. They were able with their

sensing equipment to record a shock pressure of more than fifty times the hydrostatic pressure on the wall.

Further effort by Bagnold (1939), in England corroborated the findings of De Rouville, Besson, and Petry (1938). Bagnold conducted a laboratory experiment in which he used pressure sensors within a vertical wall to study the breaking wave impact and secondary pressures. He was successful in recording the impact pressure of short duration and theorized that it was a result of air being compressed between the breaking wave face and the vertical walled structure. He suggested that the trapped air was compressed rapidly and was the reason for the existence of the short duration shock pressure. Bagnold compared his laboratory results with the field results of De Rouville, Besson, and Petry and found little agreement. In comparison his results were much higher than those of the field results of 1938. Bagnold offered a suggestion for this difference as being due to the significant irregularities of the sea surface in the field as compared to the controlled environment of the laboratory. He went on to formulate an expression for the maximum impact pressure.

$$P_{max} = \frac{2.7 \rho u^2 k}{Dt} \qquad (1)$$

where Pmax is the maximum pressure, ρ is the mass density of water, u is the horizontal velocity component of water striking the wall, k is the length of the column of water and is assumed to be 1/5 the wave height, and Dt the thickness of entrapped air between the wave face and wall.

Research continued through the years to investigate the

occurrence of impact pressures associated with breaking waves. Most of the studies dealt with the interaction of breaking waves on various vertical wall type structures in laboratory wave tanks, with a few field studies of ocean wave action on experimental test facilities. Investigation by Minikin, (1946), Denney, (1951), Ross, (1953), and Nagai, (1960), are just a few of such studies which contributed to man's knowledge of breaking waves on vertical walled structures.

2.2 Laboratory Studies of Breaking Wave Forces on Piles

As mentioned in section 2.1, the early work in the study of breaking waves dealt strictly with pressures exerted on vertical wall type structures in the laboratory and breakwaters in the field. Attention was shifting to study not only the pressures on vertical structures but to investigate breaking wave force effects on other structures such as piles.

One of the early works into the matter of breaking wave forces on piles was accomplished by Morison, Johnson, and O'Brien, (1953). Their study consisted of both laboratory and field tests to determine the total wave force on different pile sizes, shapes and configurations. Morison, and O'Brien, (1950), developed an equation to determine the total force past an object in non-steady fluid motion

$$F = 1/2\, Cd\, \rho A\, u^2 + Cm\, \rho\, Vm\, (du/dt) \qquad (2)$$

where Cd = coefficient of drag
ρ = fluid density
A = projected area of object perpendicular to the velocity

u = undisturbed fluid velocity relative to the object
Cm = coefficient of mass
Vm = volume of displaced fluid
du/dt = acceleration of the fluid relative to the object.

Use of the above equation required that both the coefficient of drag and coefficient of mass be determined experimentally. To apply the above expression to a vertical pile in an oscillatory wave system in a non-uniform flow field with respect to time the equation had to be modified and then integrated over the length of the pile. The final form of the total force equation as derived by Morison, Johnson, O'Brien (1953) was:

$$F = \pi \rho \frac{D\,H^2}{T^2} L \left\{ \pm Cd\, K_1 \cos\theta + Cm\, K_2 \frac{\pi D}{4H} \sin\theta \right\} \qquad (3)$$

where
$$K_1 = \frac{\frac{4\pi d}{L} - \frac{4\pi S}{L} + \operatorname{Sinh}\frac{4\pi d}{L} - \operatorname{Sinh}\frac{4\pi S}{L}}{16\,(\operatorname{Sinh}\frac{2\,d}{L})}$$

$$K_2 = \frac{\operatorname{Sinh}\frac{2\pi d}{L} - \operatorname{Sinh}\frac{2\pi S}{L}}{\operatorname{Sinh}\frac{2\pi d}{L}}$$

L = wave length
H = wave height
T = wave period
D = pile diameter
S = distance above bottom
d = depth of still water

Morison, Johnson, and O'Brien (1953), performed many tests on different type piles under different wave conditions. Several tests were run in the laboratory with a pile impacted upon by

breaking waves. The findings were significant as quoted in their paper; "the departure of actual conditions from the assumed conditions of equation (3) was too great to justify use of the equation in the interpretation of results in breakers. The results showed maximum forces produced by a breaker or incident breaker greatly in excess of the forces corresponding to the orbital motion described in equation (3). Similar results were obtained for field tests. In the concluding recommendations of their report they suggested "investigation should be made of breaking waves in model structures including the development of force recording equipment". With that recommendation future researchers would attempt to design test equipment to record and analyze forces exerted by breaking waves on piles.

Hall (1958) developed a dynamometer to enable calculation of total moment and force of a breaking wave. He realized from the work of Bagnold (1939), that in order for a dynamometer to work properly in the recording of breaking waves, the dynamometer would have to be extremely sensitive to capture the sudden impact force reported by earlier investigators. By measuring the force at the two reaction points, located at each end of the pile, the total force could be calculated. Many runs were performed with the pile located at different positions along the sloping bottom of the wave tank to measure forces prior to breaking, breaking directly on and breaking afterward. Hall was able to capture the sudden impact force shown in Fig.(1) as the large spike on the strip chart record. No analytical explanation was given for his results. He did report that " the maximum force affecting a pile is extremely sensitive to the point of breaking of the wave and

that " it is possible to utilize resistance wire strain gauges in the design of a dynamometer for measuring model wave forces".

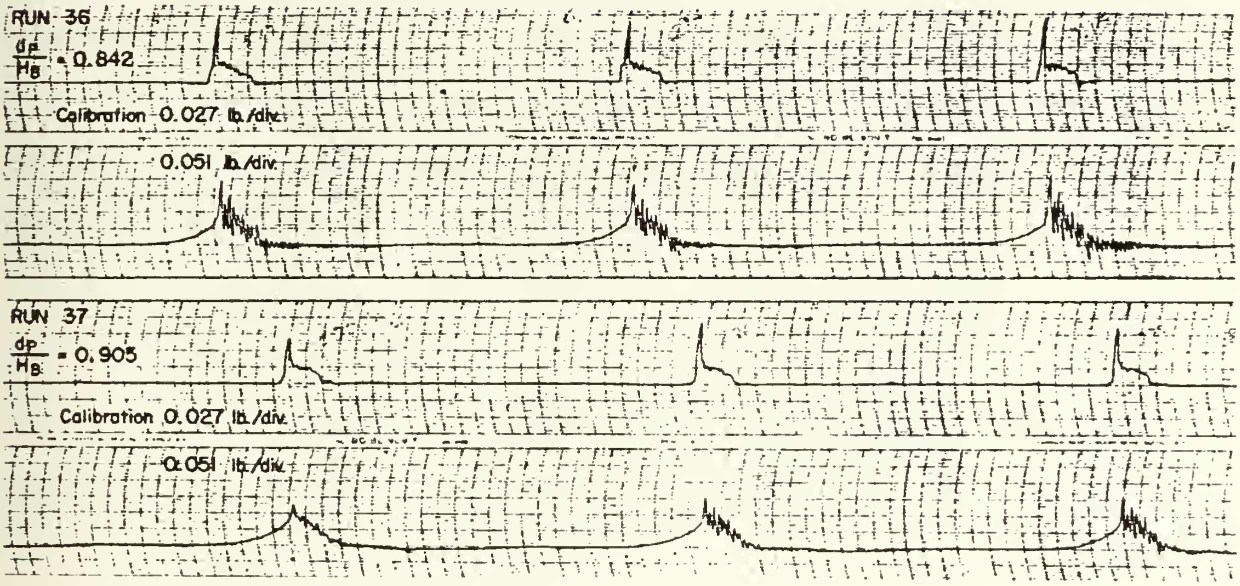


Figure 1. Breaking Wave Force Record (Hall, 1958)

Measurement of wave action on a laboratory pile was also performed by Friest (1962). He believed that the use of Morison's equation (3), to calculate wave forces on a pile was futile. He stated " the most popular approach to the solution has been through a relation in which the force exerted on a cylinder by wave action is expressed as the sum of a steady state drag force and an inertia force. The relation has the dubious distinction of containing two coefficients that must be determined experimentally. It is not clear why some investigators have chosen to pursue the coefficients rather than make a straightforward analysis and presentation of rather extensive experimental data ".

Friest tried to measure the wave action of spilling type

breakers through the use of a pile instrumented with a single pressure transducer. He was able to position the sensor vertically in the water column and measure the spilling breaker pressure of the wave. Several tests were run at different still water depths and the pressures recorded. This experiment failed to mention anything about the existence of an impact force as observed by previous investigators.

Goda, Haranaka, and Kitahata (1966), developed an equation which tried to accurately describe breaking wave forces on a pile. They developed a third term to be added to Morrison's equation (2), which accounted for the impact force exerted by breaking waves.

$$F(\text{impact}) = W\ D\ Hb\ Kb\ \lambda\ (1 - t/\pi \tau b) \qquad 0 < t < \tau b \qquad (4)$$

where $Kb = Cb^2 \pi Nc \,/\, 2g\ Hb^2$: Impulsive force factor

$\tau b = D \,/\, 2\ Cb$: Duration time of impact force

Hb = breaking wave height
Nc = crest height above still water level
λ = curling factor of breaking wave (function of bottom slope and relative depth).

Goda et al. experimentaly verified their equation by observing breaking waves on several different piles and found good agreement between their equation and laboratory results.

The last known published work involving laboratory experiments of breaking wave forces on a pile was accomplished by Watanabe and Horikawa (1974). What they did was to test Goda et al.(1966) equation for applicability to a large diameter pile vice a slender pile. Two test piles of differing diameter were

manufactured and instrumented using a slide bearing assembly and an upper and lower strain plate. Wave force acting over the length of the pile was transmitted to these strain plates and recorded. Several waves of different period and wave height were run past the test piles and the corresponding forces recorded. A sample record of a plunging breaker impacting on the larger diameter pile is shown in Fig. (2). The short duration impact force is the spike portion of the figure and looks similar to that recorded by Hall (1958).

Examination of the recorded forces with the calculated forces obtained using equation (4) was found to be smaller than the observed forces. Watanabe and Horikawa put forth an explanation for this observation. They suggested that the phase lag between particle accelerations and the inertia forces are considerable and must be considered when estimating the drag and inertia coefficients, of equation (4).

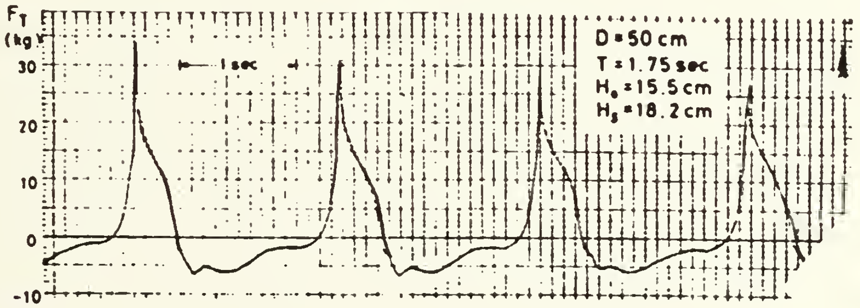


Figure 2. Plunging Breaker Force Record (Watanabe et al. 1974)

One current study is underway by Dean, Torum, and Kjeldsen (1985) to study wave forces including breaking wave forces on a pile instrumented with 26 force transducers. These force

transducers were positioned vertically along the length of the pile spaced at 5 cm increments. The force transducers were able to measure local forces in the in line as well as transversal direction as shown in Fig. (3). Formalized results are pending publication and should prove to be very interesting.

2.3 Field Studies of Breaking Wave Forces on a Pile

Very limited information exists concerning the effects of breaking wave forces on a pile exposed to actual sea conditions. Such information is essential in understanding breaking wave forces on a pile and concerted effort in this area needs to be expended.

Two noteworthy studies of breaking wave forces on piles are that of Snodgrass and Hall (1951), and Miller, Leverette, O'Sullivan, Tochku and Theriault (1974).

Snodgrass et al. (1951), used a 3-1/2 inch diameter brass pile hinged to a pair of foundation piles jetted into the sand bottom and supported at the top by two retaining bars instrumented with strain gauges. They were able to obtain the the total moment about the hinge point by multiplying the force at the calibration point by the lever arm distance. The total force measured at the calibration point was the sum of localized forces along the pile from the surface to bottom of the pile.

Miller et al. (1974) investigated breaking wave pressures exerted on a 6 foot aluminum flat plate instrumented with 5 strain gauge mounted aluminum diaphrams, mounted at one foot intervals. Their intent was to obtain a vertical distribution of breaking wave pressure along the length of the pile structure, as

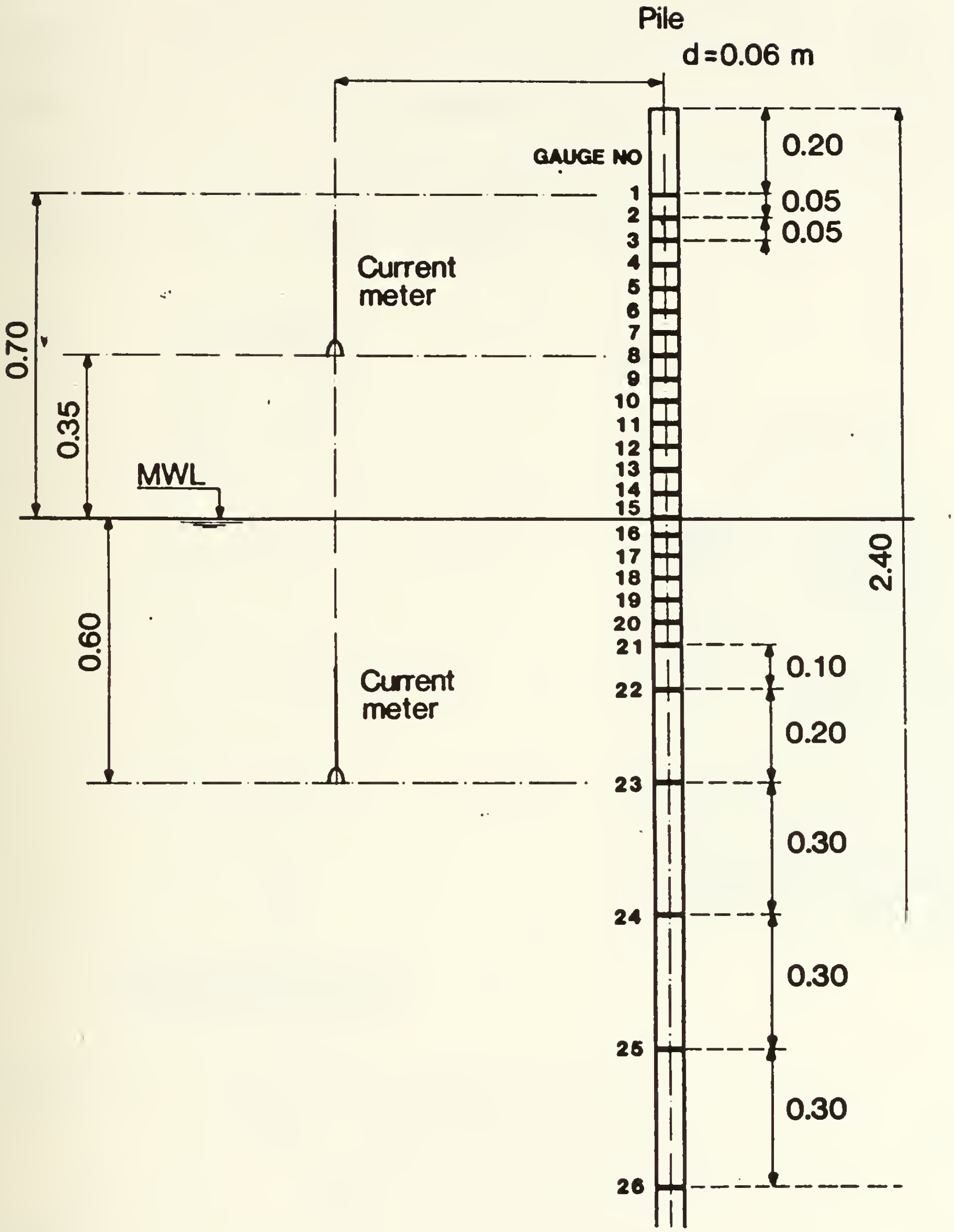


Figure 3. Instrumented pile of Dean et al. (1985)

well as to measure the short duration impact pressure.

Plunging breaker wave pressure data collected from the outer shore of Cape Cod verified the existence of a short duration impact pressure evidenced as the spike at sensor number one as shown in Fig. (4). In addition the vertical pressure distribution at each of the different sensor positions of Fig (4) shows the variation within the breaker column.

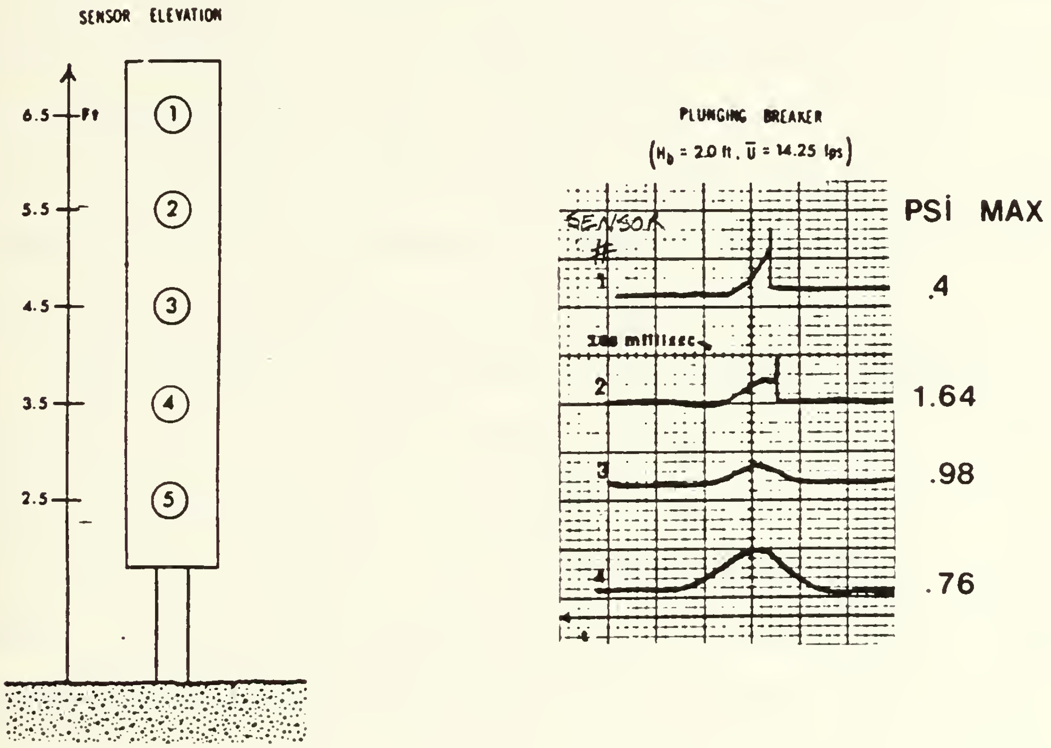


Figure 4. Plunging breaker pressure distribution at different sensor elevations of Miller et al. (1974).

For an in depth and comprehensive literature survey on breaking wave forces on piles, the reader is referred to an engineering report by Panigrahi (1985). The report reviews past efforts of previous investigatiors, current theories, and provides suggestions for future research.

CHAPTER 3

DESIGN OF FORCE MEASURING DEVICE

As mentioned in the introduction the purpose of this experiment was to develop a force measuring device capable of recording the rapid rise impact force and oscillatory force induced by a plunging breaker along a section of a pile. By designing such a device one would then be able to combine several of these to simulate a pile recording the force distribution along the length of the pile. To formulate such a design it was necessary to consider several criteria deemed essential and combine these to yield a complete and operational device.

The initial conditions imposed upon the design were:

1. Manufacture a device sensitive enough to respond to the impact forces of plunging breakers and yet sturdy enough to withstand repeated abuse by waves striking the device.

2. The device had to allow for movement in the vertical direction. To study the plunging breaker forces it was incumbent to be able to move the device vertically up and down within the wave in order to obtain some idea of the force distribution of the wave.

3. It was also a desire to be able to determine the directionality of the impacting waves. Designing the device to do so one would be able to determine the direction of wave impact simply from an analysis of a given set of data collected with the device.

4. Operational simplicity was also an important consideration taken into account. The intent was to design a

gauge simple to fabricate, instrument, and operate.

5. Possible field usage was considered. The gauge designed for the laboratory had to be capable of being scaled up in size and usable in actual field conditions.

An initial design was formulated and consisted of a hollow circular section supported by three flex members attached to a support column as shown in Fig. (5) and Fig. (6). The hollow section which represented the outside diameter of a pile was constructed of thick walled 3 diameter inch plastic PVC pipe. A section of PVC pipe was cut to a dimension of 1.5 inch in length. One hole was drilled at every 120 degrees mid length around the circumference of the section. These holes would serve as attachment points for the flex members which will be discussed later. The support member was constructed of 3/4 inch rigid electrical conduit. An 8 inch length of conduit was obtained and one hole drilled every 120 degrees around the circumference of the conduit, mid length. As with the PVC section above these holes would serve as attachment points for the flex members. Three 3/4 inch threaded nuts were driven down inside the section of conduit and allowed the gauge to be screwed both up and down in the vertical plane.

Brass flex members were fabricated and served as the surface on which a set of strain gauges would be placed in order to measure the deflection of the gauge produced by the plunging breaker waves. The flex members consisted of 0.10 inch thick brass strips 1 5/8 inch long and 1/2 inch wide. Each end of the brass flex members was bent 90 degrees and a 1/8 inch hole drilled for attachment to both the conduit support member and the

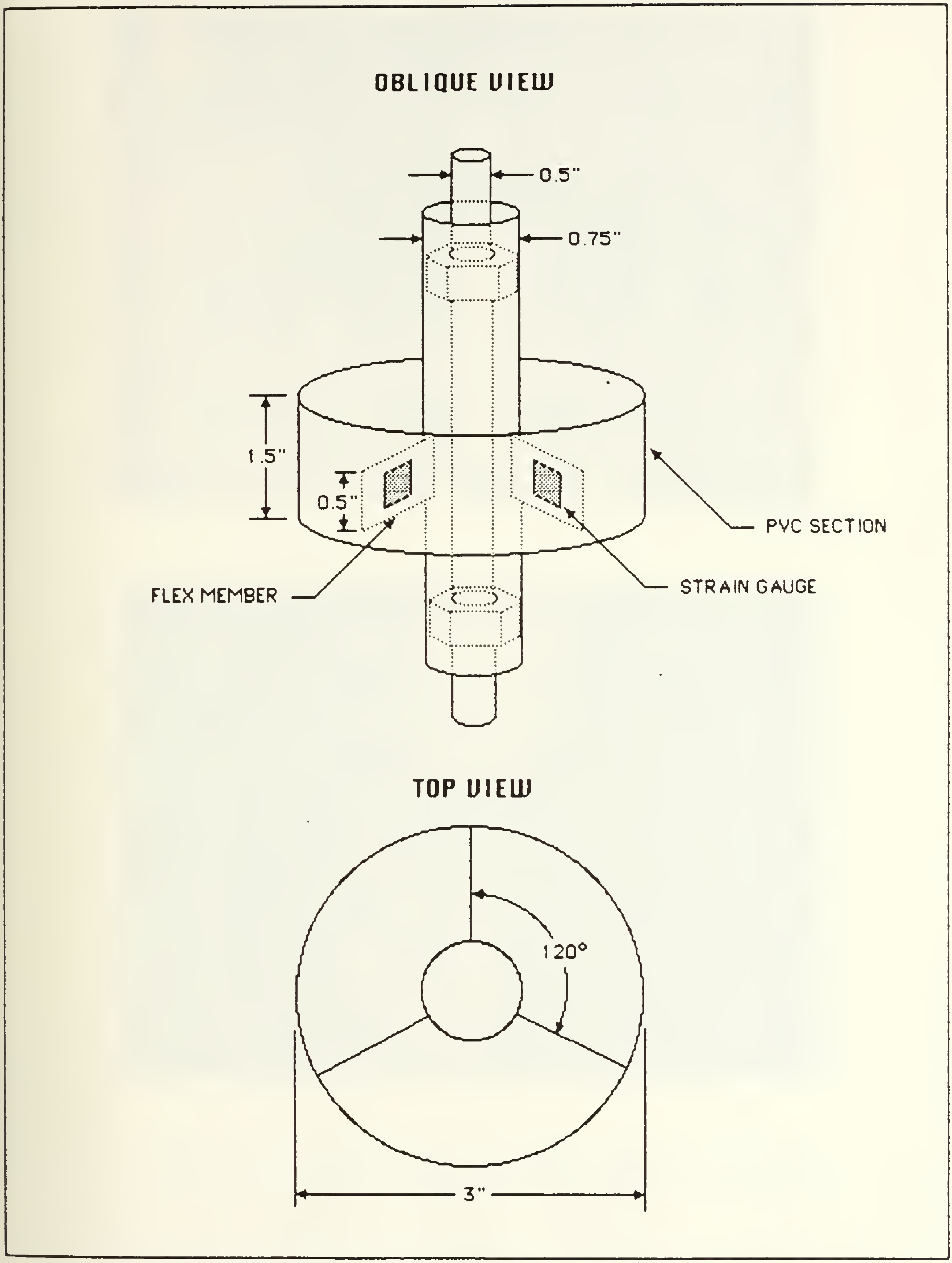


Figure 5. Graphic of Force Measuring Device

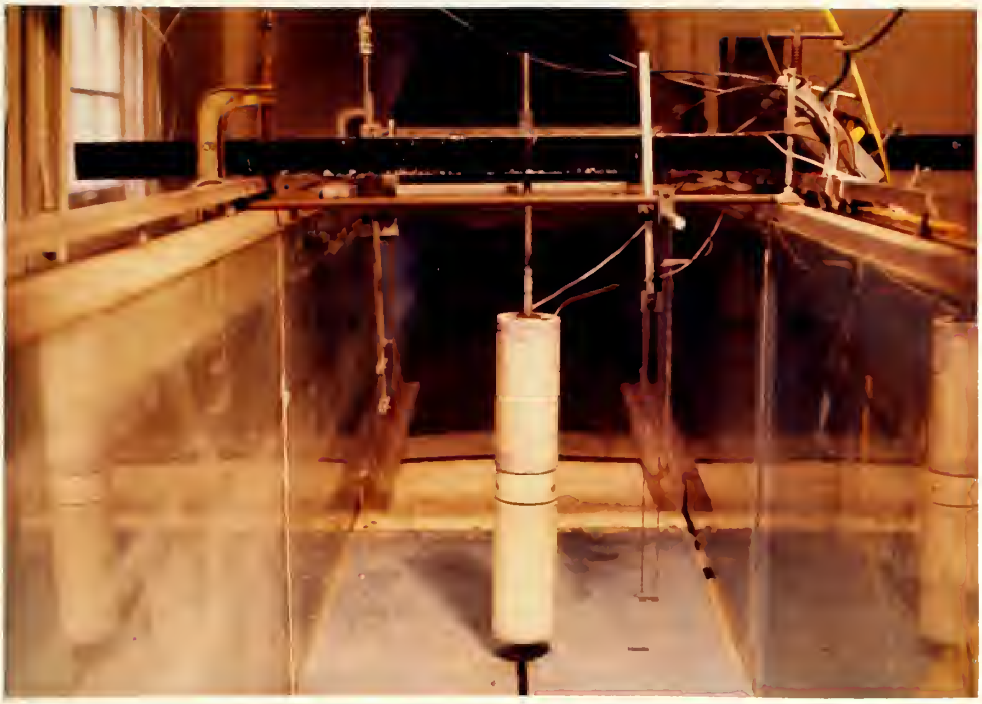


Figure 6. Photographs of force measuring device

PVC section. Rivets were driven through each end of the flex member to rigidly connect it to both the conduit support member and PVC section.

Reasoning behind the 120 degree spacing of the flex members was to allow for an ability to determine the directionality of impacting waves. The intent was that with the symmetrical spacing one would be able to determine both the X and Y components of wave force for each member and by summing these forces determine the direction of the plunging breaker.

Several similar type gauges were constructed with different materials but found to be inadequate mainly due to insufficient support strength, or excessive deflection of the outer surface of the gauge which was unacceptable. The selection of PVC for the outer surface and brass flex members proved to be the best combination and yielded good results.

After fabrication the device was instrumented with six Micro Measurement 120 ohm strain gauges. It was known that the range of wave force to be designed for was approximately two to six pounds. With that knowledge proper selection of the strain gauge was possible. Each flex member had two strain gauges, one placed on either side to measure deflection. The completed electrical schematic is shown in Fig. (7). When instrumented the device formed a 1/2 bridge electrical circuit. A terminal board was constructed to allow for conversion of the gauge from a 1/2 bridge assembly to a full bridge assembly as shown in Fig. (7). This conversion was made possible using two 120 ohm resistors added to each strain gauge circuit. With this option it was possible to use several different recording devices in which to

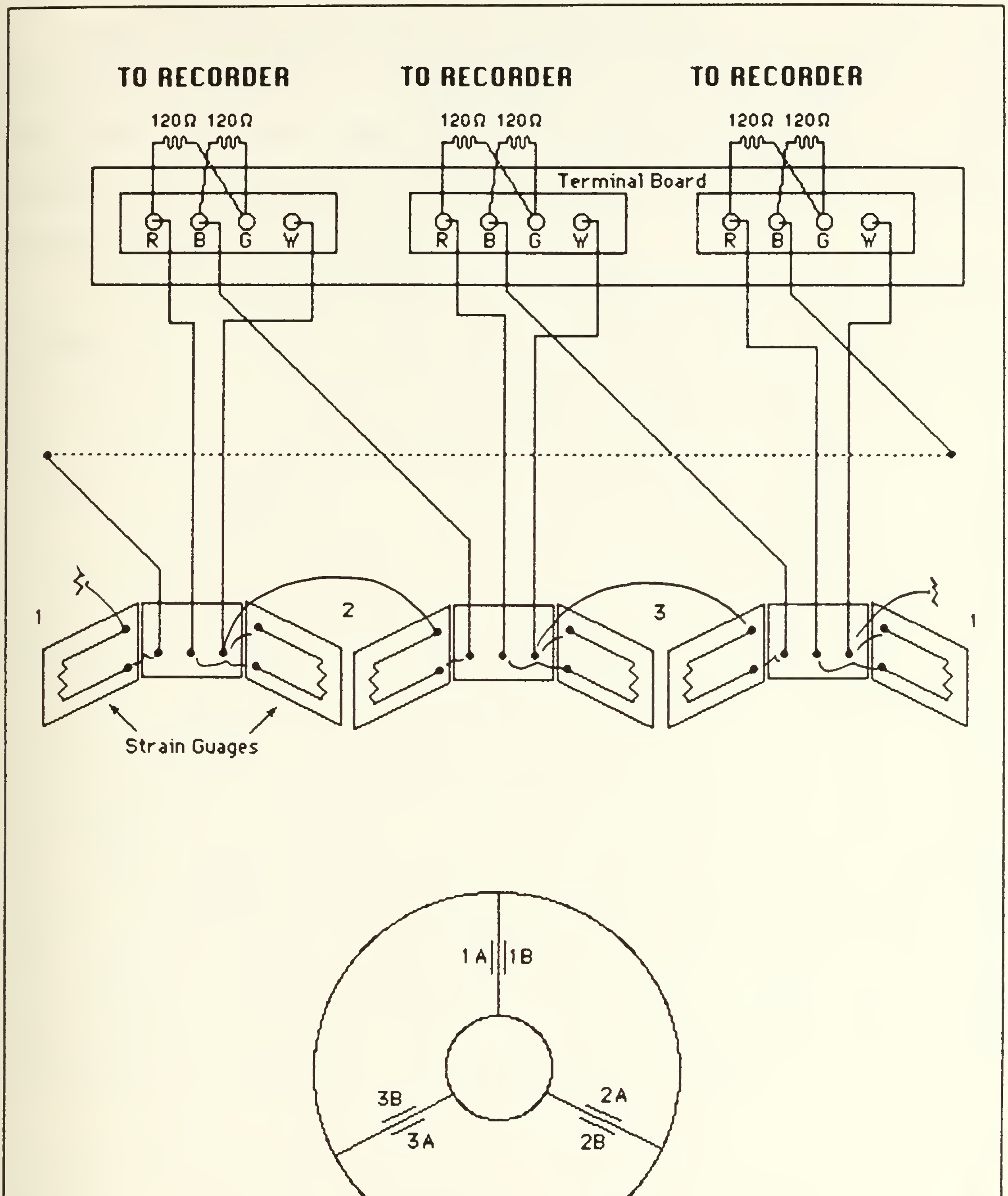


Figure 7. Electrical schematic of force measuring device

collect data.

The instrumented gauge was supported vertically on a 36 inch long 5/8 inch diameter threaded rod, allowing for movement in the vertical direction. The threaded rod was secured to a cross member above the tank and allowed one to rigidly fix the rod and gauge assembly in the tank.

It was recognized that a calibration device would also be needed to initialize the gauge prior to use. Construction consisted of an aluminum cross member rigidly fixed to the top of the wave tank and which supported two 18 inch long 5/8 inch diameter threaded rods. A lower cross member was hung from the end of the threaded rods and a pulley positioned mid length. The pulley was used to guide and support a weight assembly used in calibration, of the force measuring device, as shown in Fig. (6).

Two dummy pile sections were constructed and designed so as to butt up against the test device as shown in Fig. (6). These two dummy sections did not to touch the experimental test device but were capable of fitting flush so as to simulate a complete pile. By minimizing the spacing between the dummy sections and test device it was felt that a minimum of wave action inside the test device would be experienced. By reducing this interference confidence was gained in the experimental results.

CHAPTER 4

EXPERIMENTAL APPARATUS

The entire experiment was carried out in a glass walled water-wave flume Fig.(8). The flume measured 120 feet long 3 feet deep and 2 feet wide. The bottom of the flume consisted of 3/16 inch steel plate with 3/8 inch glass panel walls for observation purposes.

A false floor was constructed of 1/2 inch treated plywood and positioned at the aft end of the wave tank. The 35 foot long floor was fabricated with a slope of 1:35 and would cause shoaling which generated plunging breakers to be measured. The floor was securely anchored through use of both weights and steel rods extending from the wood sloping floor to an anchored crossmember above the tank. A 2 feet X 1/2 inch slot was cut in the last two feet of the floor and allowed precise positioning of the test device within the breaker zone.

A pendulum type wave generator was used to generate the test wave, Fig. (8). Several adjustments could be made to the generator to vary the wave amplitude and period. The paddle of the wave generator was connected to a 1.5 foot diameter drive disk by a stainless steel shaft. The drive disk was rotated by an adjustable gear unit which was positioned above the paddle assembly. The unit was rated at 3 horsepower at 1800 rpm.. A variable speed rectifier control allowed for adjustment of the

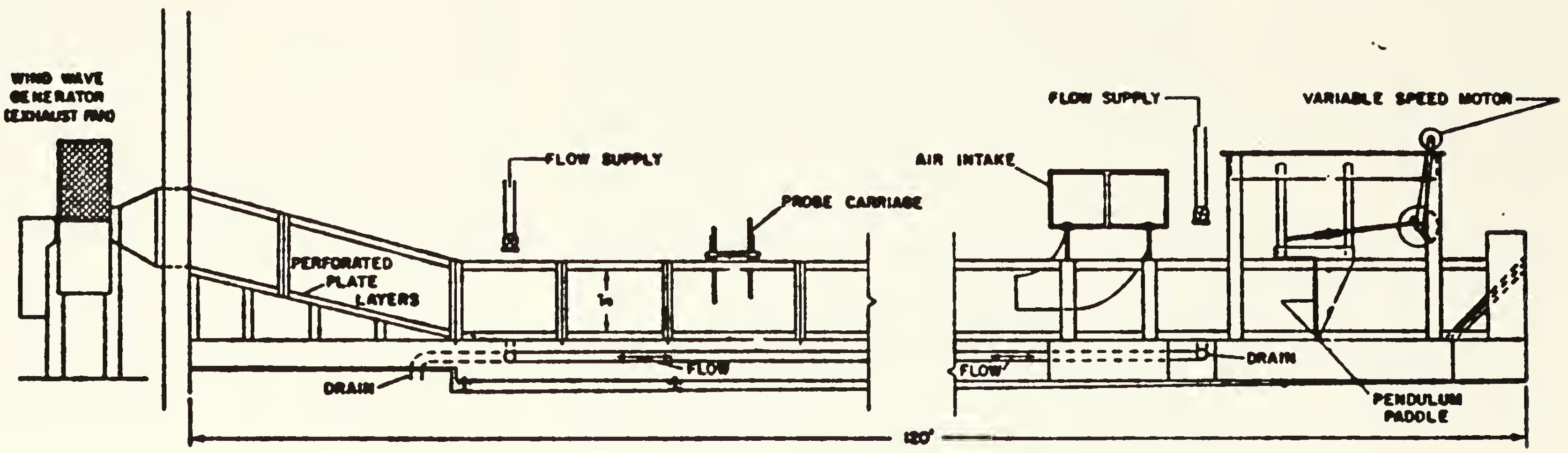


Figure 8. Glass walled water wave flume

drive unit. The wave period desired could be obtained by adjusting the rectifier which would vary the speed of the variable drive unit and enable a wide range of wave periods to be generated. An adjustment also existed on the wave paddle which allowed one to vary the wave height by modifying the stroke length of the paddle. A screw assembly on the drive disk enabled one to vary the stroke length by simply adjusting an internal key assembly on the drive disk.

A 4 inch thick wave filter consisting of wire mesh was positioned 10 feet in front of the paddle to help filter out any small irregularities of the wave created by the paddle. Likewise a wave absorber was placed aft of the wave tank to reduce wave reflection within the tank. The absorber consisted a graduated layering of chemically coated horse hair in the wave runup zone. Eight feet of absorber was used with a thickness of 2 inch at the front edge of the absorber graduated to 8 inchs at the back of the absorber.

Two Seasim Autocompensating Wave Height gauges each 400 millimeters long, of stainless steel construction were used as shown in Fig. (6). The capacitance type wave height gauges were positioned in the tank and connected to a Seasim Processor Module viewed in Fig. (9). Appendix III contains detailed visual of all experimental equipment used.

The Seasim processor module transmited a carrier frequency to the wave probes and then processed the return altered frequency. The analyzed signal was then sent to a suitable recording device which for this experiment was a Hewlett Packard 17402A Oscillographic Chart Recorder.

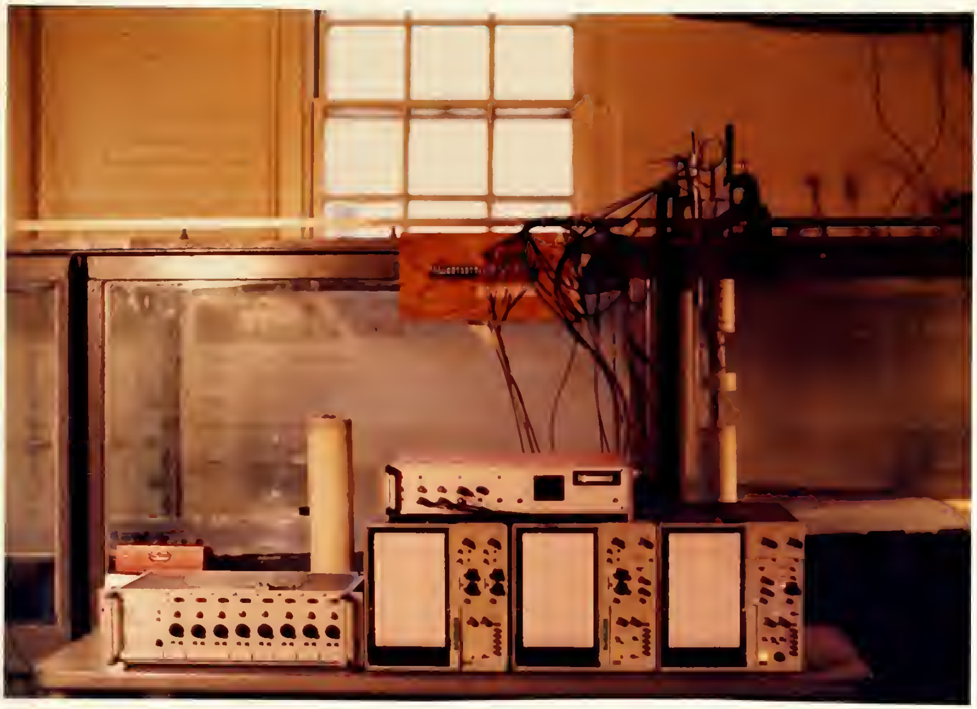


Figure 9. Photograph of experimental apparatus

The recorder was fitted with both a HP 17402A Low Gain DC preamplifier for wave height measurements and a HP 17403A AC preamplifier used for wave force measurement. The Low Gain preamplifier received input from the Seasim Processor Module and provided a deflection drive output to the recorder and chart display. The AC preamplifier provided an excitation voltage to the strain gauges and processed the return signal. The return signal was amplified, compared with a reference signal, filtered and passed to the recorder for chart display.

Velocity measurements within the breaking wave were also investigated. A bi-directional micro-propeller current meter (Mic), manufactured by Hydrel Aps of Denmark was used. The micro-propeller (Mic) consisted of a 5 mm diameter three bladed propeller suspended between a stainless steel frame on jewel bearings. Two electrodes were fixed to the stainless steel frame and were used to sense propeller rotation rate and direction of rotation. An analog voltage output signal was sent to both electrodes with the return signal processed and transmitted to a Hp 17402A recorder for display. The Mic was capable of being accurately positioned vertically in the wave crest and used in conjunction with both the wave height gauge and force measuring device to investigate plunging breaker characteristics.

CHAPTER 5

EXPERIMENTAL PROCEDURES

5.1 Calibration

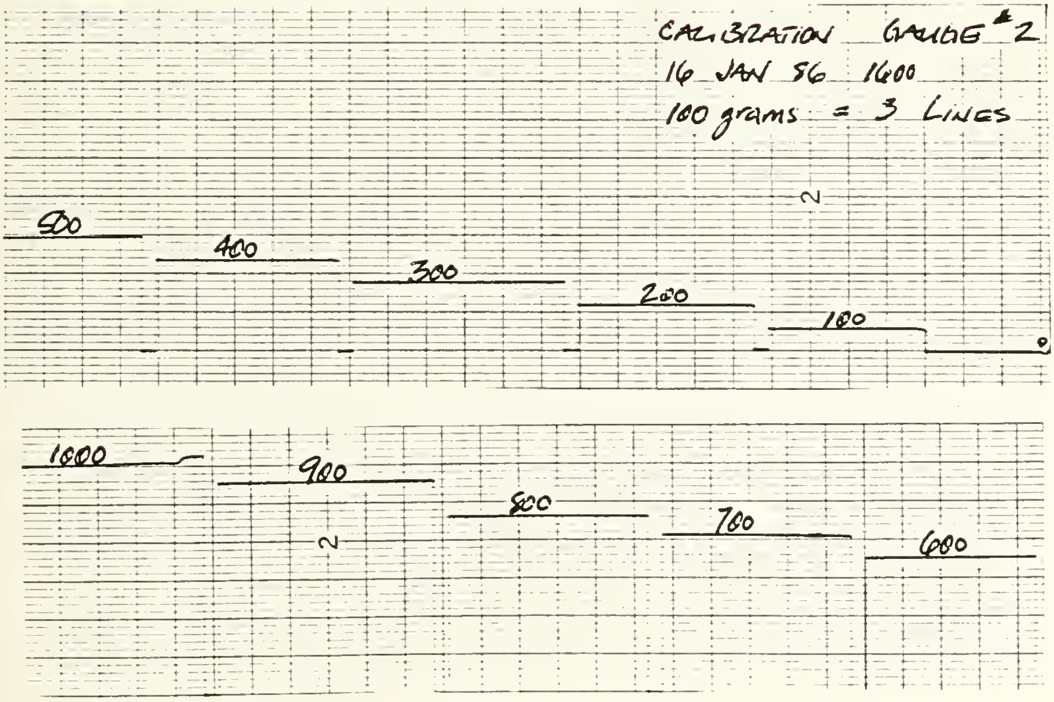
Before data collection could begin with the wave force measuring device several preliminary steps had to be accomplished. First experimentation with the wave tank was necessary to find an appropriate setting of the motor rectifier, paddle position, stroke length and water depth to ensure that a plunging breaker could be created to break directly upon the test device. Attempts were made to create a deep water wave at the paddle which would shoal and break. After several tries it was found this to be impossible due to the frequency with which the paddle was required to operate, causing severe turbulence and a wave form that was unusable. A long shallow wave was found to produce the largest plunging breaker in the breaker zone. The water depth at the break point was 9.5 inchs above the sloping bottom with a 10 inch plunging wave height at breaking. The variable rectifier setting was noted and used for subsequent experiments. Appendix II contains experimental test data of the four runs performed.

Having determined a wave which produced a plunging breaker the instrumentation to be used in data collection had to be calibrated. Two wave height gauges were used to record the wave height and profile before shoaling and the wave height and profile at breaking upon the test device. The two wave probes were connected to a Seasim Processor module which analyzed the

return signal from the wave height probes and passed this signal to a HP 17402A strip chart recorder for observation. The wave probes were calibrated according to published instructions and a zero reference position found. Once a reference position on the strip chart recorder was located deviations from such would allow determination of the wave profile.

The test gauge was positioned in the glass walled wave flume and securely fastened to the top of the wave tank using C-clamps and to the bottom of the sloping bottom with several retaining nuts as shown in Fig. (6). The gauge was leveled to ensure plumbness. Leads from each of the three flex members were routed to a terminal board which converted the 1/2 bridge strain gauge circuit of the test device to a full bridge configuration as viewed in Fig. (7). Individual leads from the terminal board were then connected to the recording instruments. Two different recording instruments were used to analyze the calibration characteristics of the gauge. One was a Hewlett Packard 3497 Data Acquistion unit the other a Hewlett Packard 17402A strip chart recorder. The Hewlett Packard 3497 was used mainly due to the accuracy that could be obtained from the digital display. The calibration assembly described in chapter 3 was securely fastened in front of the gauge and leveled. A thin wire was run over the pulley on the calibration assembly and fixed to the gauge as shown in Fig (10a). A graduated series of weights were then suspended from the wire and a corresponding reading taken on the recording instrument in use. This procedure was repeated numerous times with the gauge rotated to various different positions and the corresponding calibration records noted.

A



B

Figure 10. Photograph and sample record of calibration

Results of calibration using the data acquistion unit may be found in Appendix II. During calibration it was found that due to the inaccuracies in the gauge construction, the ability to determine the direction of wave impact would not be possible. The exact positioning of the flex members at 120 degree segments around the interior of the PVC section was found to be critical and any deviation from such yielded a non-linear relationship which prohibited useful data collection in this experiment.

To correct this flaw the gauge was positioned in such a way that a linear relationship with one flex member could be obtained and that position was used throughout the different experimental tests. Calibration of the gauge was accomplished using the strip chart recorder with a sample calibration record shown in Fig. (10b). The resultant calibration plot is shown in Fig. (11), for both flex member two and the combined plot of all three flex members. During this calibration phase the exact positioning of the gauge with respect to orientation within the tank was very critical. To ensure exact positioning each and everytime a plumb line was drawn across the front face of the gauge and also a reference line above the gauge on the supporting cross member. Each time the gauge was moved a plumb bob was used to align the two reference marks and guarantee consistent positioning of the gauge.

5.2 Data Collection

Having calibrated the necessary instruments accurate data collection could be obtained. For comparison purposes the wave height data and the force measurement data from flex member

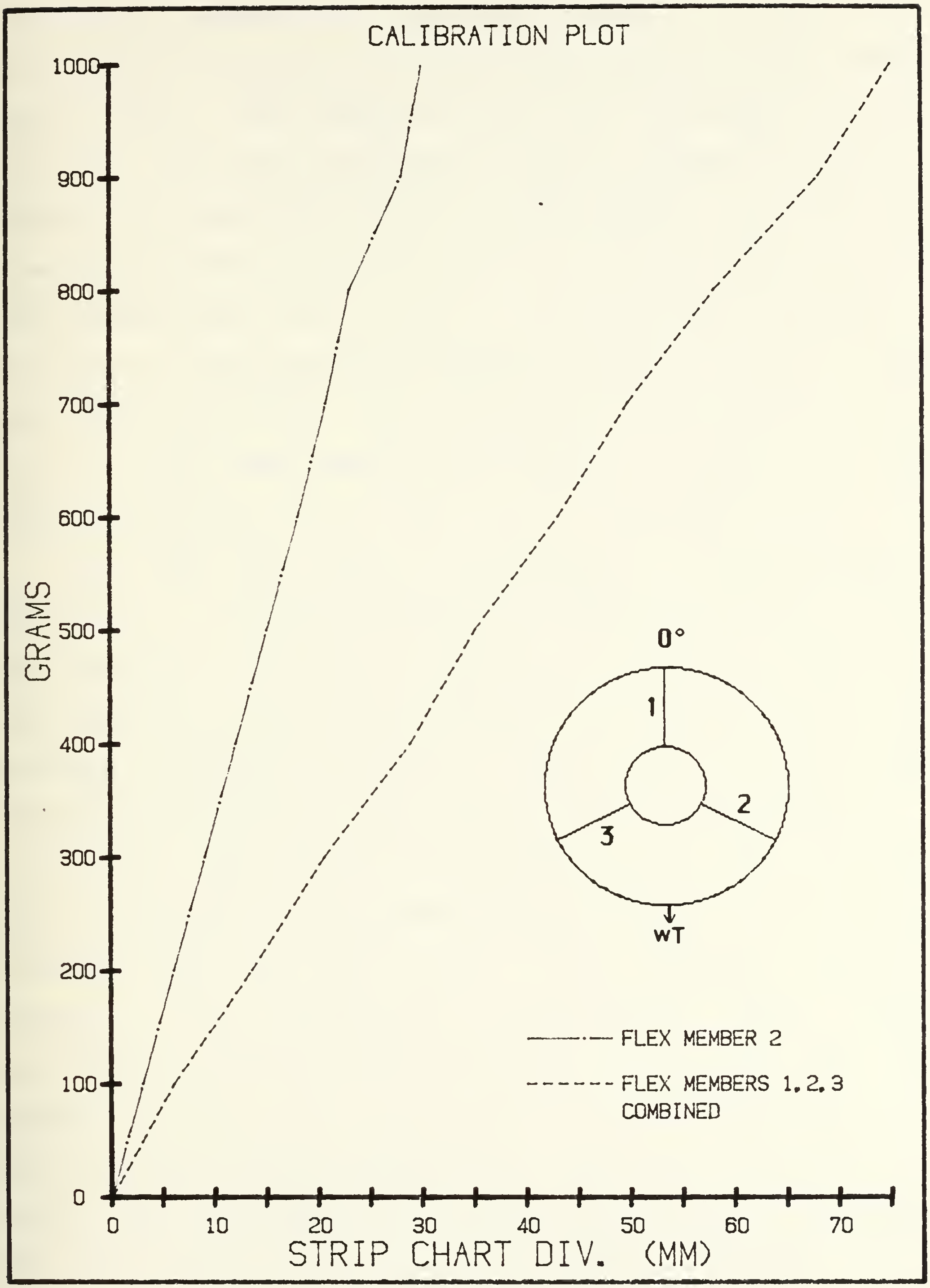


Figure 11. Calibration Plot of Force Measuring Device

number two were output to a HP 17402A recorder. The non-breaking wave data was recorded on a separate recorder. A third recorder was employed to capture the force measurements of flex members one and three. Even though the data from flex member number one and three were not to be used it was of interest to note the results. The wave height probe was positioned on the side of the experimental force measuring device and securely fastened to the cross member above the wave tank. The force measuring device and two dummy pile sections were anchored to both the top of the wave tank and sloping bottom. By turning the threaded rod through the center of the test device it was possible to move the device vertically and position it accurately in the wave column.

With the test device positioned and leveled, data was collected. To ensure consistent results the period of the wave was measured just prior to shoaling. It was incumbent that there be no deviation during different test runs of this critical parameter. Ensuring the period of each run was exactly the same, confidence was gained in the validity of the data collected.

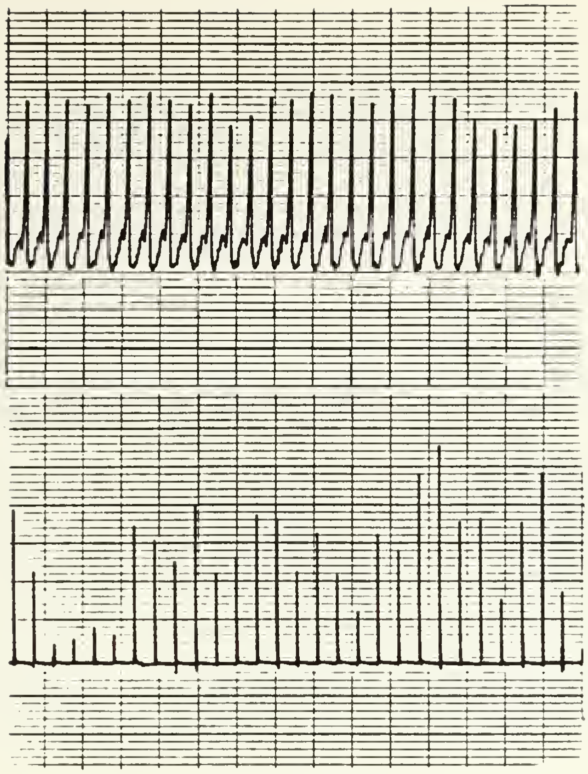
As the generated wave propagated down the wave channel a small reflected wave was observed propagating in the reverse direction back up the channel. This phenomena created an obstacle in the collection of consistent data, causing oscillation of the point where the wave broke. The oscillation seemed to be cyclical in nature and caused the plunging wave to break forward of the test device, then on the test device and finally aft of the device. Little could be done to compensate for this problem except to pay careful attention to the recording instruments and observe exactly when the wave broke on

the test device and note the resultant force and breaker profile as displayed on the strip chart record.

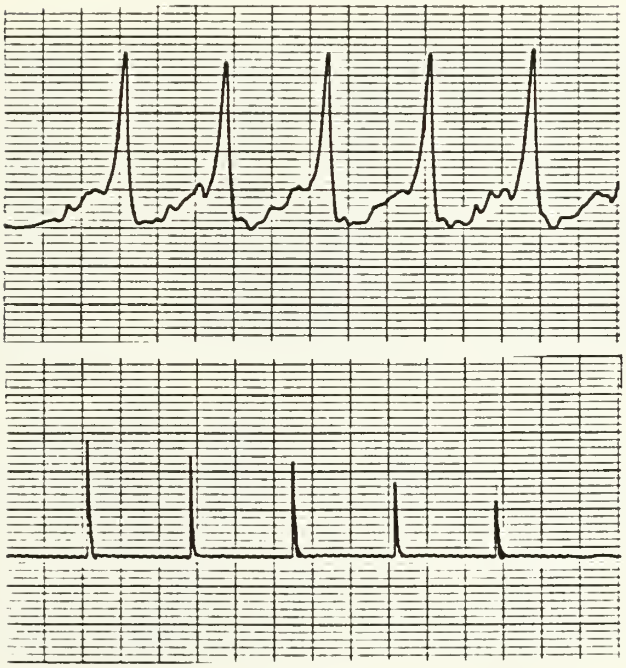
Several different paper speeds on the recorder were used to collect the data as shown in Fig. (12) and Fig. (13). Doing so it was apparent that the most useful wave and force information could be collected at a speed of 125 mm/sec. Operating the recorder at that speed , excessive amounts of expensive recorder paper were used, thus long term data was collected at a slower speed of 1mm/sec or 5mm/sec and useful in observing wave force magnitude only. Little usable data with reguards to wave profile was obtained at the slower recorder speeds. To ensure adequate data a compromise between the different speeds had to be achieved.

Upon completion of data collection at a given height the test device was positioned to the next lower increment. As mentioned it was essential that the device be aligned with the previously delineated alignment marks and plumbed. Having accomplished proper alignment of the gauge the wave generator was started and the exact same procedure as above repeated always ensuring the wave period of each run remained the same. Measurements of plunging wave forces were recorded at one inch increments starting at 7.5 inchs above the still water level (SWL), and working downward to 0.5 inch above SWL. This was done to capture the force distribution within the crest of the plunging breaker.

Once the necessary incremental runs were completed the experimental apparatus was moved to a position just forward of the sloping bottom. This repositioning enabled comparison of

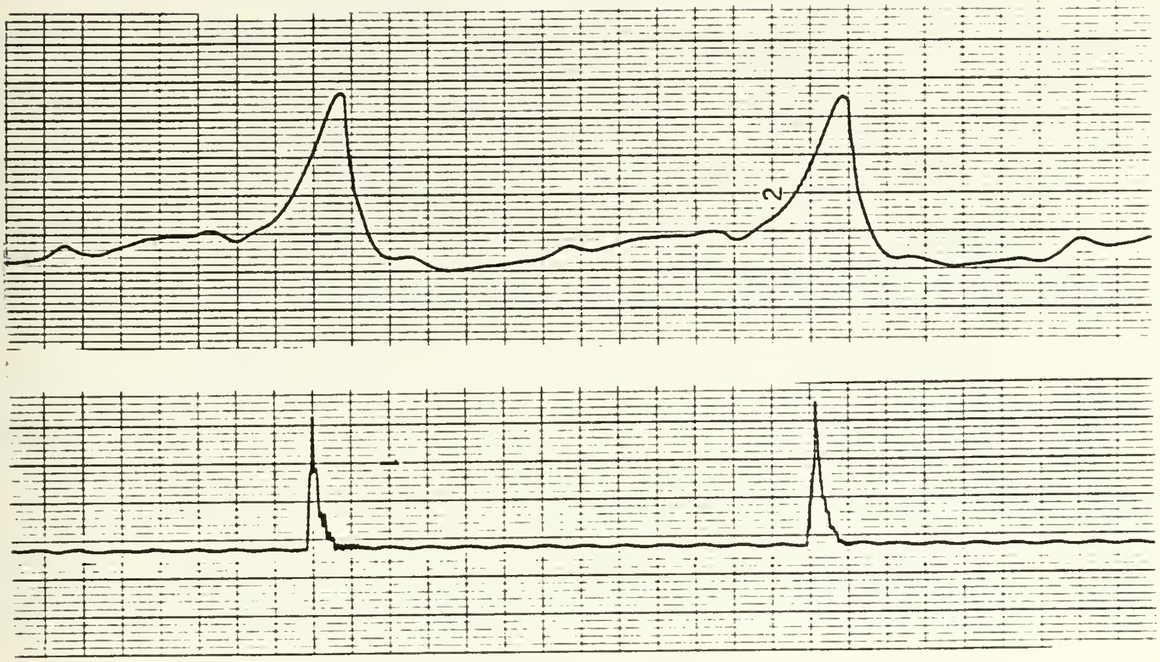


1 mm/sec

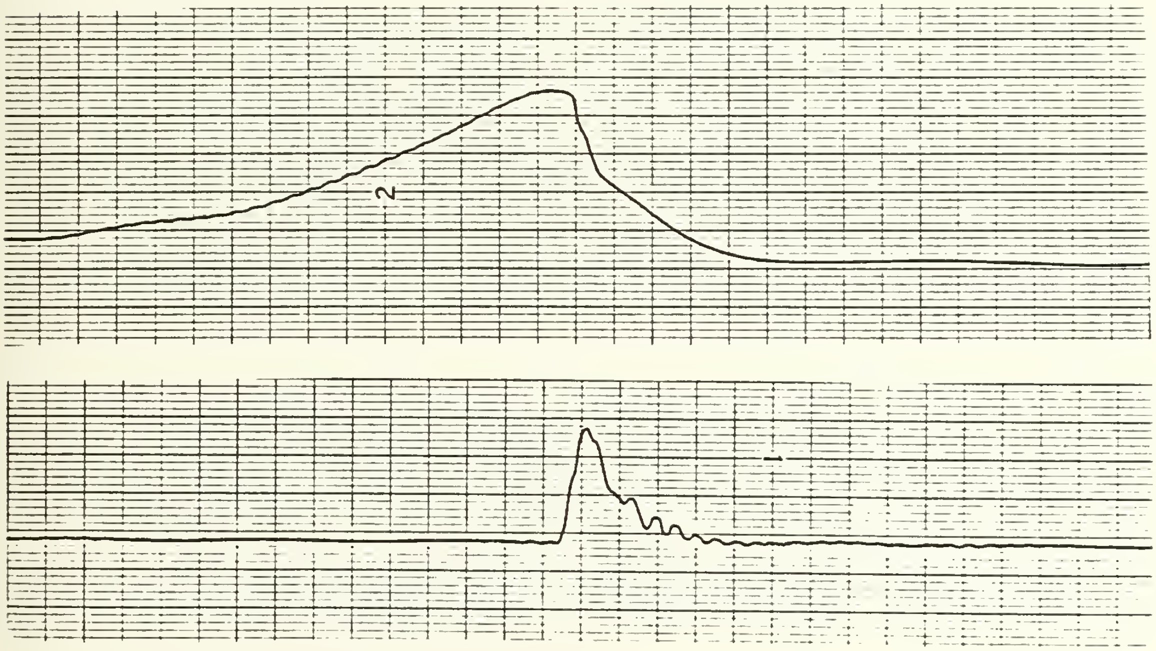


5 mm/sec

Figure 12. Sample wave force recordings at 1 and 5 mm/sec



25 mm/sec



125 mm/sec

Figure 13. Sample wave and force recordings at 25 and 125 mm/sec

wave forces exerted by the same generated wave but prior to shoaling. Again the equipment was positioned calibrated and measurements taken, ensuring that the same experimental procedures were followed. It was noted that the effects of reflection experience during the breaking wave portion of the experiment were much less and did not affect the non-breaking force as it had done in the breaking wave portion of the experiment.

With two sets of data, one at breaking and the other before breaking, the experiment was run again to validate the accuracy of the experimental procedure.

CHAPTER 6

ANALYSIS AND DISCUSSION OF DATA

6.1 Operational Analysis of Test Device

Four test runs using the experimental force measuring device were performed. Two runs were forward of the sloping bottom and the other two were in the plunging breaker zone. Tabulated results of the runs are shown in Appendix II.

One of the major efforts of this project was to construct a force measuring device which would accurately record the impact pressure of a plunging breaker. Viewing the results of the force record shown in Fig. (15), it can be seen that the device did capture the impact force as indicated by the short duration spike followed by a decreasing longer duration secondary force. It is interesting to note that the impact force of Fig. (15), lasted approximately .016 seconds which can be determined knowing that the chart speed of the record was 125 mm/sec. The secondary force had a duration of .296 seconds and a much smaller magnitude of force.

Breaking wave force results from two other similar experiments, that of Hall (1958) and Watanabe, and Horikawa (1974) are shown in Fig. (1) and Fig. (2), respectively. Both records show a large spike indicating impact followed by a smaller longer duration secondary force. Hall (1958), tested breaking waves but did not specify which type of breaking wave he recorded. Reference was made to run number 36 and 37 shown in Fig. (1) as being a record in which the verticle face of the wave struck the pile leading one to believe the wave was probably of

the plunging type. Watanabe and Horikawa (1974) indicated that their record, Fig. (2) was of a plunging breaker and closely resembles experimental data obtained with the test device used in this report. Little comparison can be made with regard to the magnitude of force obtained with the previous two force measuring devices of Hall (1958), and Watanabe et al.(1974) and this experiments test device. Different experimental procedures, objectives and methodologies used prohibit further analysis and comparison except to note that the force records do look similar.

In summary, the force measuring device constructed for use in this experiment did work and did accurately capture the impact force of plunging breakers. The materials used were sturdy and withstood the repeated barrage of wave action. The simplistic design and ease of calibration and usage suggest this device to be an ideal candidate for further investigation, improvement and possible field usage.

6.2 Analysis of Velocity Distribution

An attempt to measure the velocity profile within the wave crest for both the breaking and non-breaking waves proved to be unsuccessful. During collection of the data the incoming signals from the instrumentation appeared to be accurate, but upon analysis it was found to be in error. The faulty data was not realized until the experiment had been dismantled and thus no attempt was made to trouble shoot the problem and gather new data.

6.3 Analysis of Plunging Breaker Data

As mentioned in Chapter 5, four test runs were performed to record both breaking and non-breaking wave data. Runs one and two measured plunging breaker forces with runs three and four recording non-breaking wave forces.

The plunging breaker forces were difficult to measure due to the existence of a secondary harmonic which oscillated fore and aft within the wave tank. This harmonic caused the wave to first break forward of the pile, Fig. (14), then at the pile, Fig. (15), transitioning to breaking aft of the pile, Fig. (16). Concerted effort was put forth to minimize this oscillation of break point. An extensive system of wave energy absorbers were placed aft of the test device in an attempt to reduce the amount of reflection traveling back up the wave channel. Little change was noticed and the experiment continued taking this effect into account. It was observed after considerable observation that the maximum impact force of the wave occured just as the vertical wave face struck the pile as shown in Fig. (15). Measurements of maximum impact force taken at increments within the vertical wave crest are tabulated in Table I-A of Appendix II and displayed graphically in Fig. (17) and Fig. (18). Table I-C and Table I-D of Appendix II, contain tabulated results of the force data converted to dimensionless pressure and are displayed graphically in Fig. (19) and Fig. (20).

As can be seen in Fig. (17) and Fig. (18), a very definite force distribution within the plunging breaker crest was evidenced. In both figures it is noted that the maximum force occurs

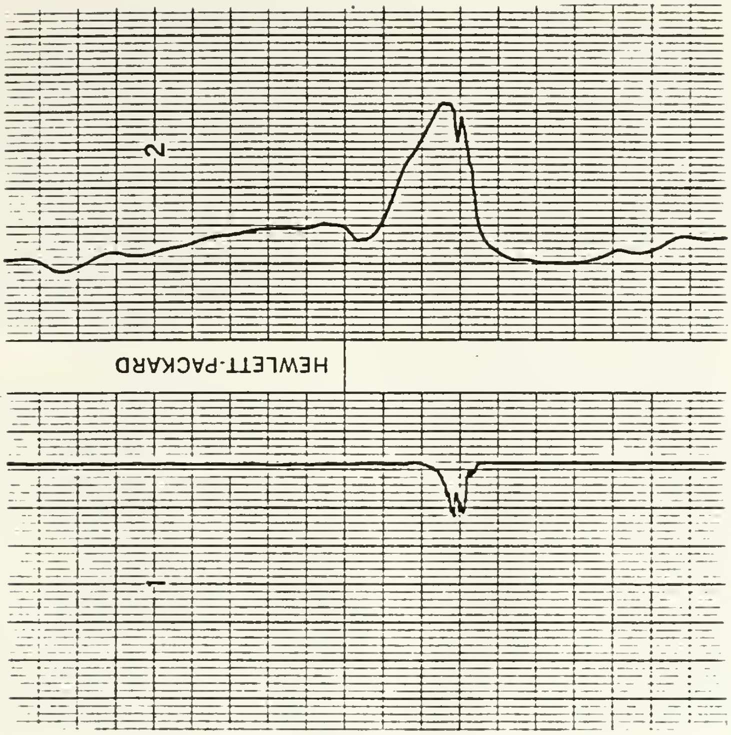


Figure 14. Strip chart record and photo of plunging breaker breaking forward of pile.

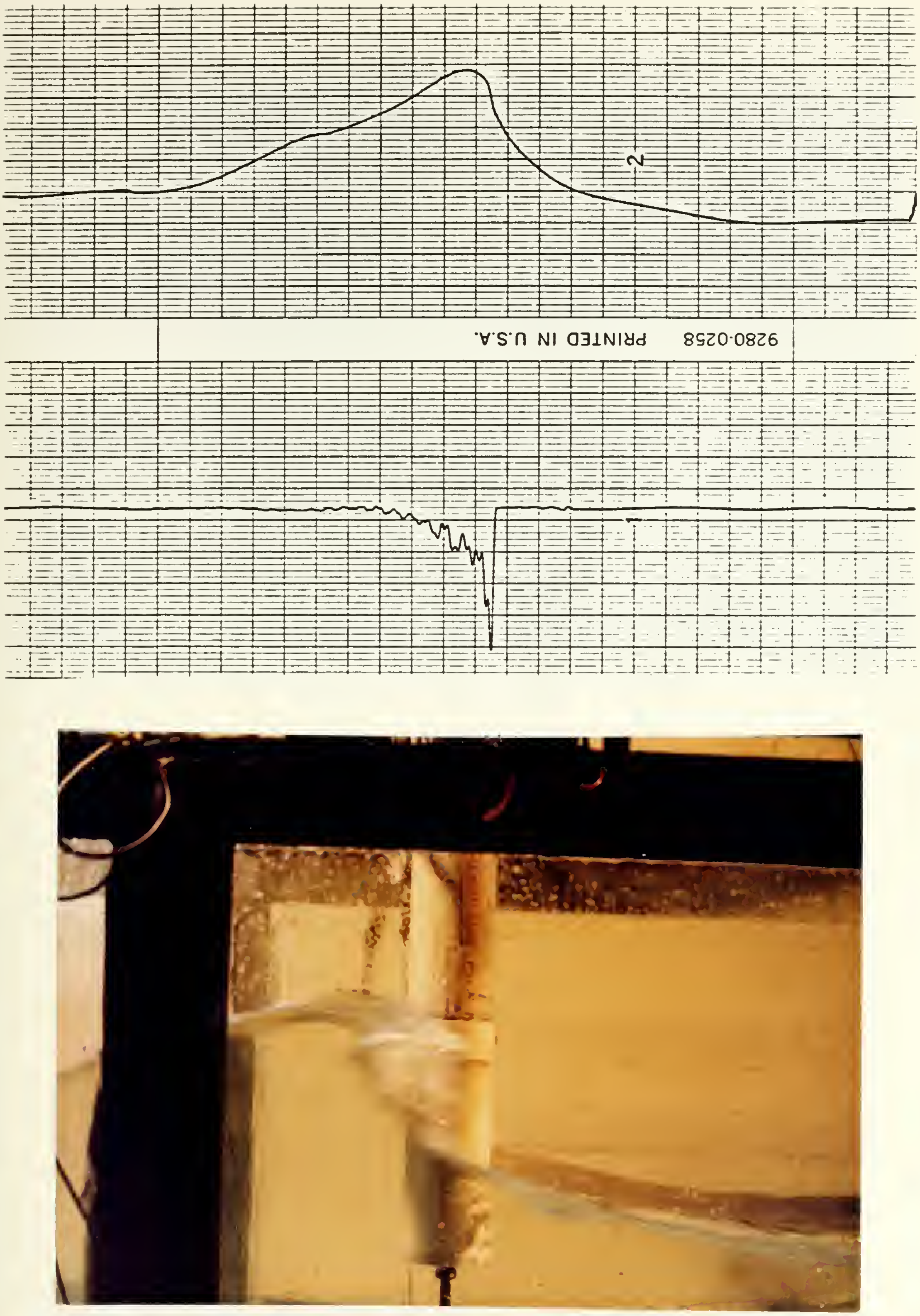


Figure 15. Strip chart record and photo of plunging breaker breaking on pile.

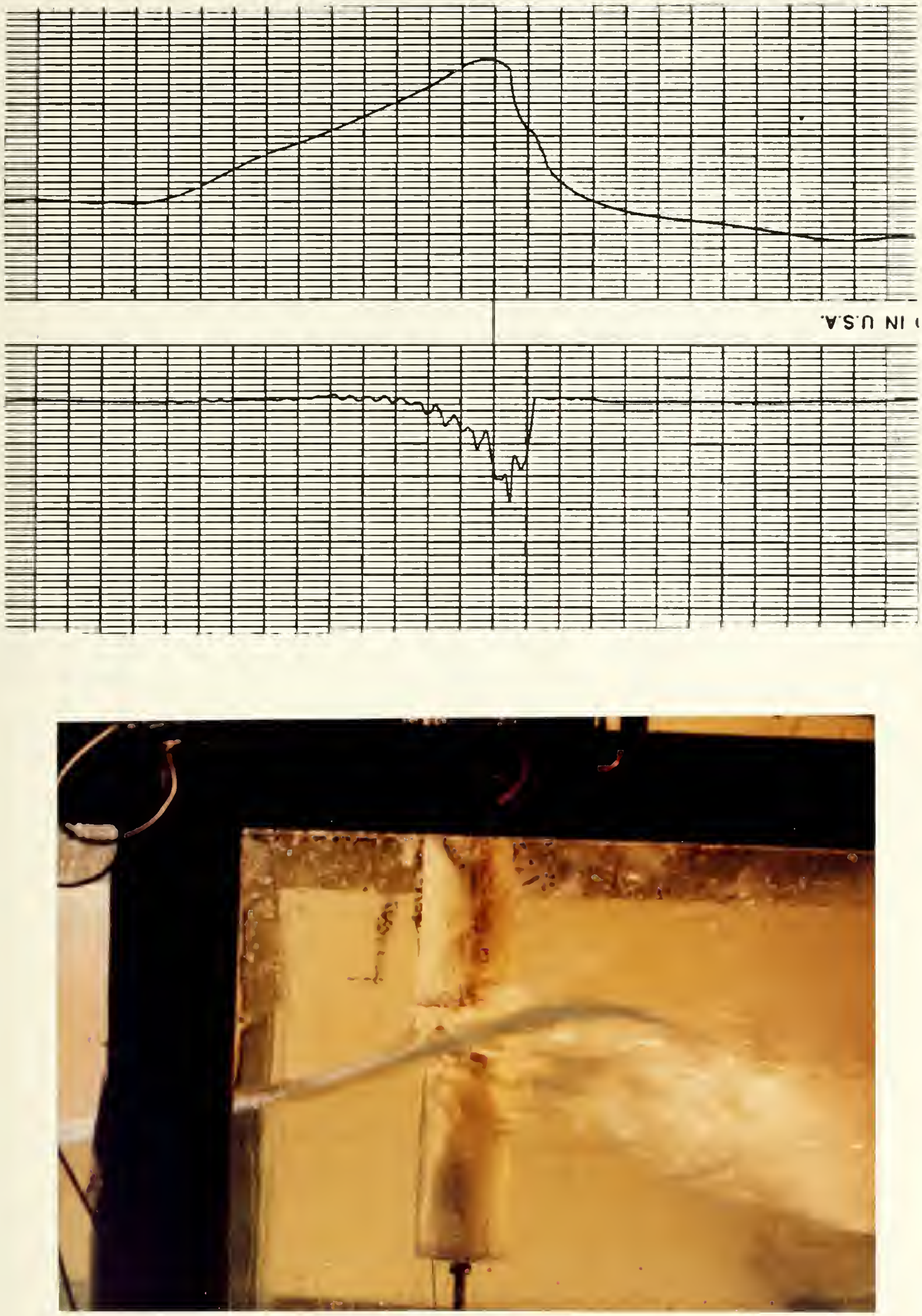


Figure 16. Strip chart record and photo of plunging breaker breaking aft of pile.

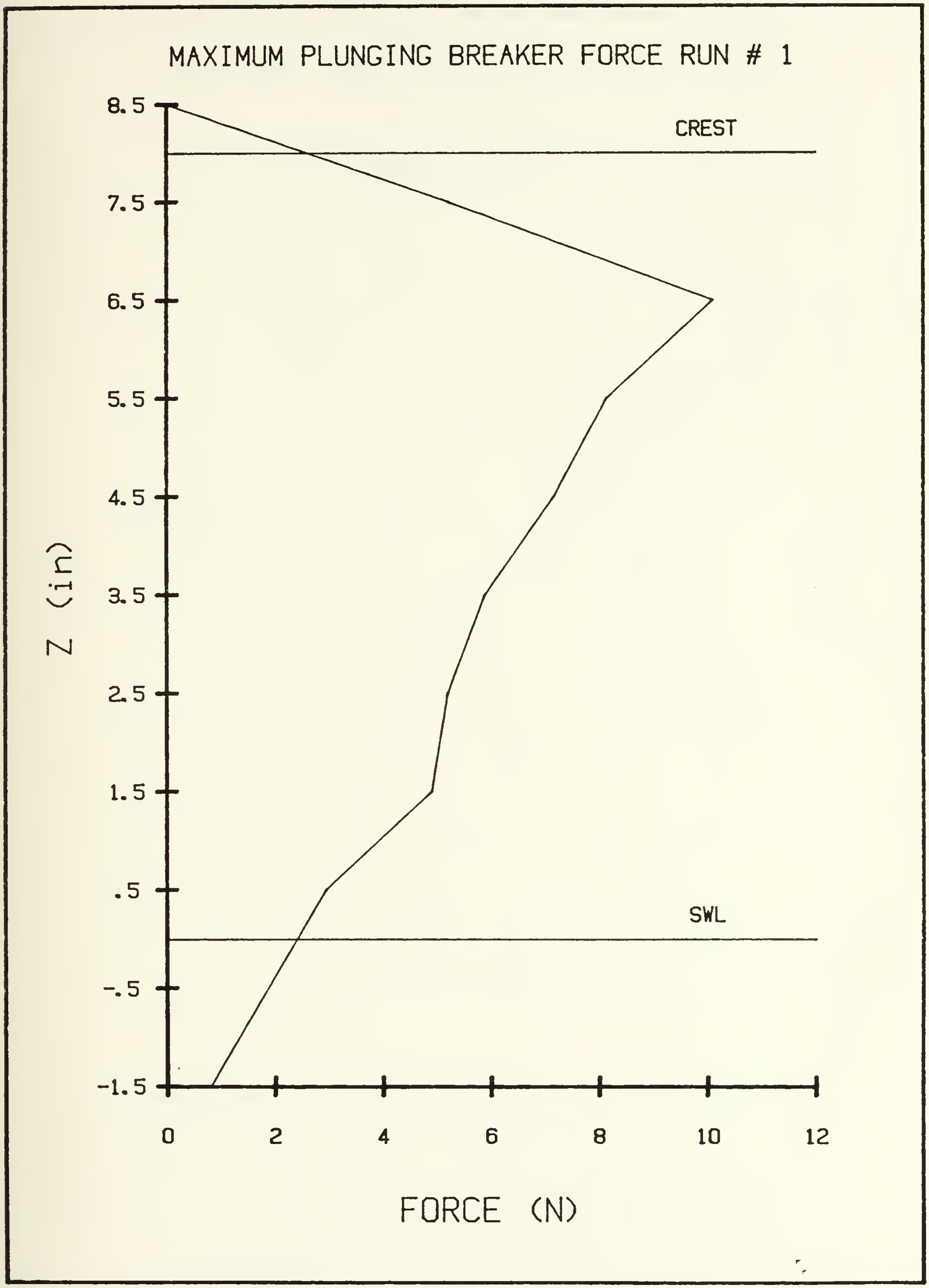


Figure 17. Maximum Vertical Force Distribution of Plunging Wave Run # 1.

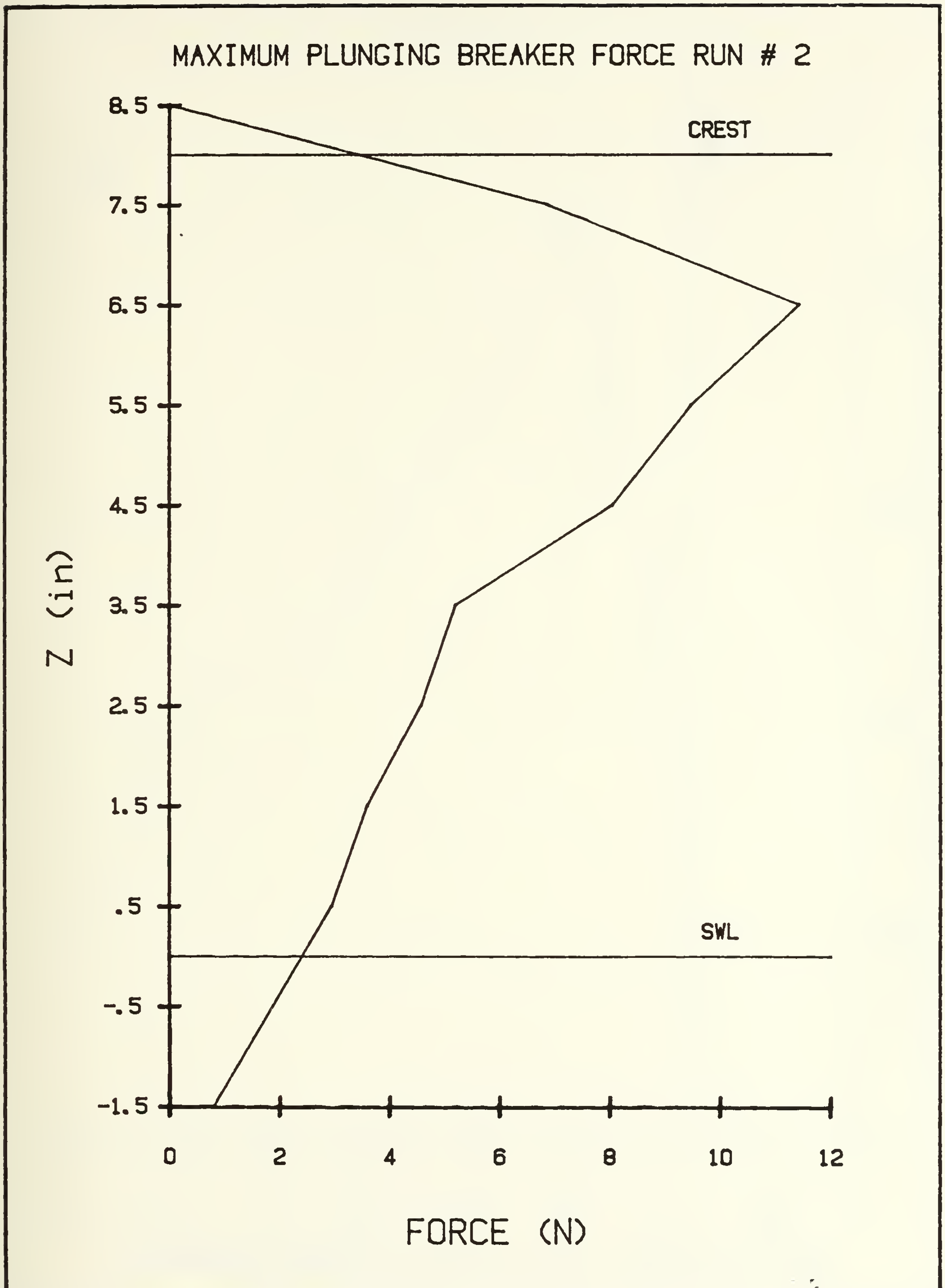


Figure 18. Maximum Vertical Force Distribution of Plunging Wave Run #2.

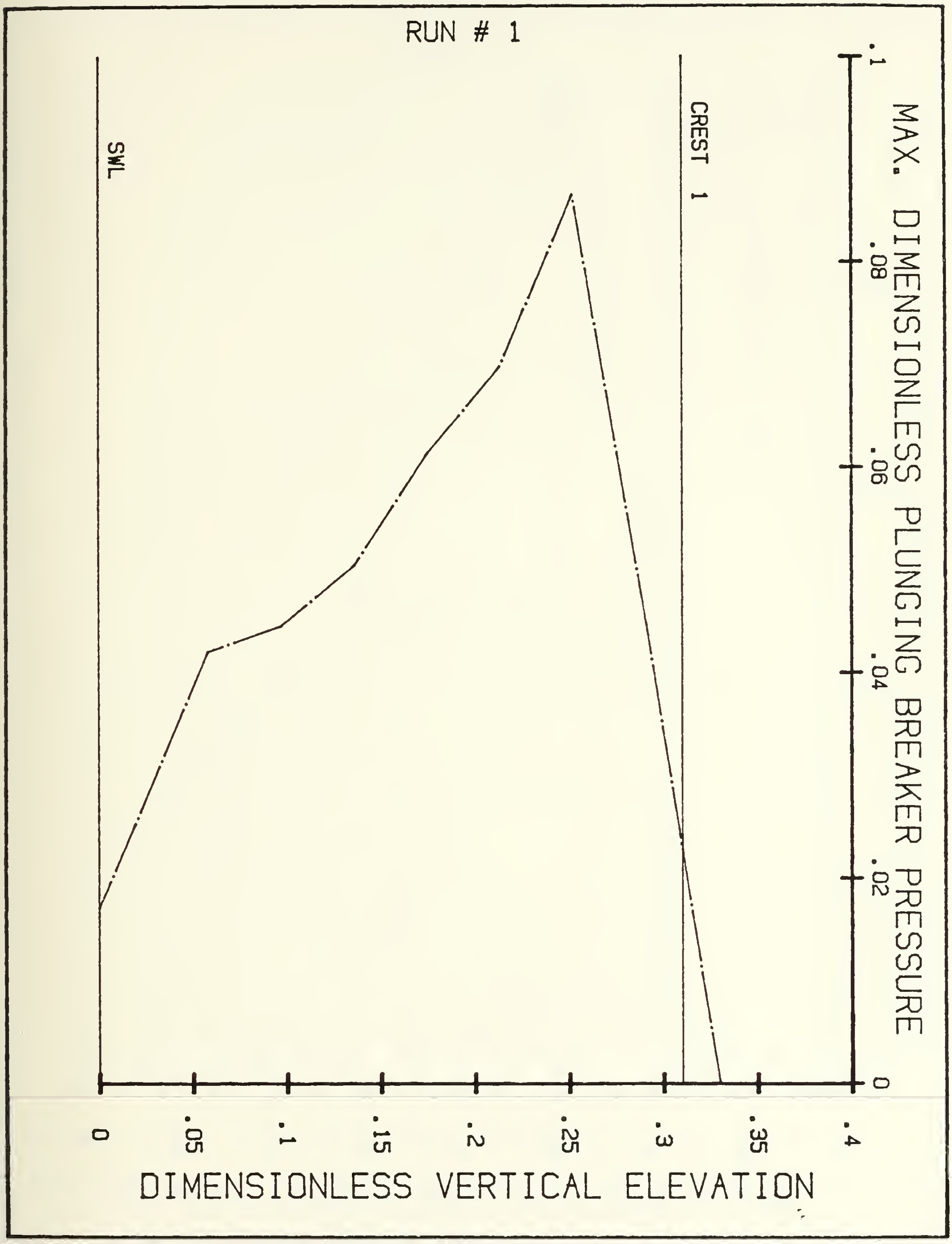


Figure 19. Maximum Vertical Dimensionless Pressure Distribution Run #1.

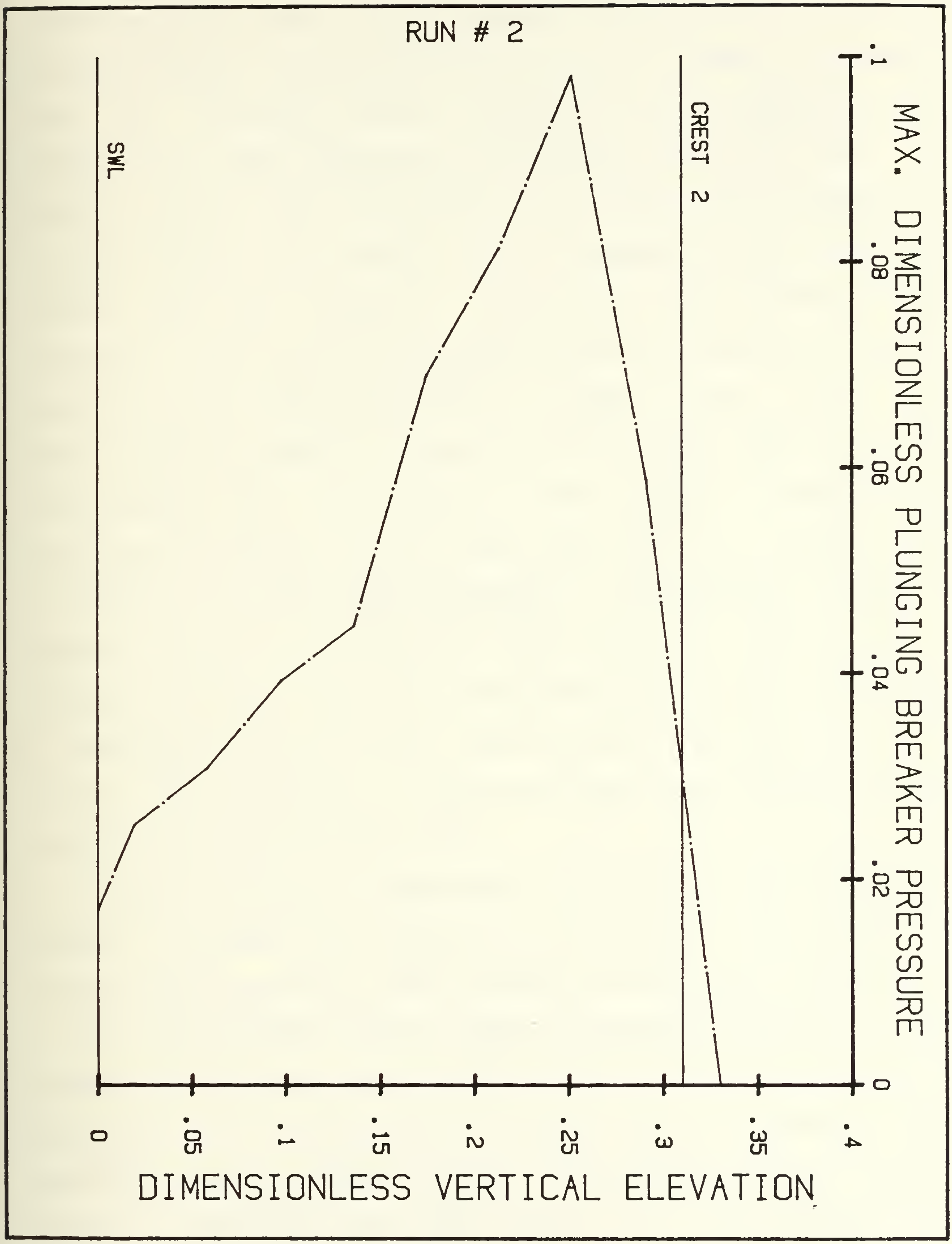


Figure 20. Maximum Vertical Dimensionless Pressure Distribution Run # 2.

slightly below the wave crest.

Comparison of the vertical pressure distribution data of a plunging breaker collected by Miller et al. (1974), as shown in Fig. (21) indicates basic agreement with the verticle force distribution data collected in this report shown in Fig. (17), and Fig. (18). Figure (21) shows the maximum impact pressure was recorded on the upper sensor, with a decrease in pressure at the middle and lower sensors. Wantanabe, and Horikawa (1974) published the verticle force distribution of a plunging breaker obtained during their experiment, as shown in Fig. (22). Once again there is general agreement with the basic shape of their distribution and that obained by this project. There is some controversy though as to the exact position of the maximum force. It appears that the data of Watanabe, and Horikawa places the maximum force at or slightly above the still water level as compared to just under the crest as obtained in this experiment. It should be pointed out that their experiment though similar in nature was different in that they studied the plunging breaker forces on a large diameter pile.

Results recently published by Kjeldsen and Akre (1985) compare favorably with results of this report. Studies of two dimensional deep water freak plunging breakers were measured with a pile instrumented with 26 force transducers placed at various increments along the length of the pile Fig. (3). This freak wave consisted of a wave group composed of 43 transient waves generated by a computer signal. The problem of a secondary harmonic affecting the break point, in this report, was eliminated in Kjeldsen's data using this computer generated wave

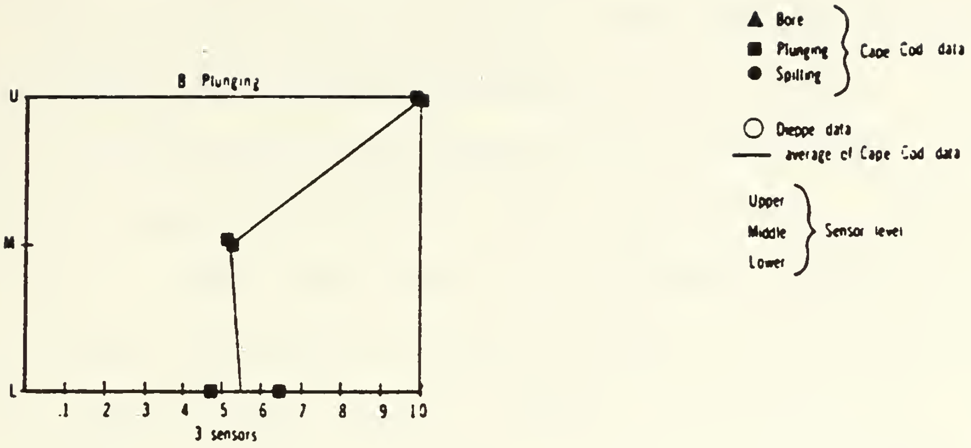


Figure 21. Vertical pressure distribution of a plunging breaker Miller et. al (1974)

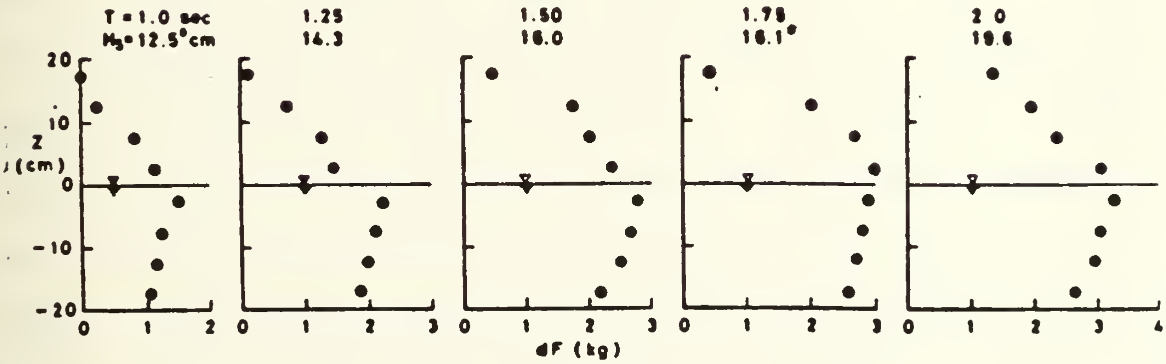


Figure 22. Vertical force distribution of plunging breaker Watanabe et al. (1974)

signal ensuring point wave impact exactly on the pile. Figure (23) shows force data of several different waves including a freak plunging breaker obtained with the instrumented pile . It should be pointed out that there are two major differences between this report and that of Kjeldsen et al. (1985). One is the vertical reference was with respect to the mean water level, vice the still water level used in this experiment. Secondly, Kjeldsen et al. (1985) data was of deep water plunging breakers whereas this report consisted of shallow water plunging breakers. Figure (23) shows force versus verticle elevation of three different waves; a plunging breaker, regular non-breaking wave and a spilling breaker. Comparison of wave A of Fig.(23), with Fig.(17), and Fig. (18), shows that the magnitude of force between the different plunging breakers is considerable. This difference exists due to the different areas, of each experiments transducers, over which the wave force acts.

Kjeldsen et al. (1985) developed a dimensionless pressure versus vertical elevation graph shown in Fig. (24). With this graph he was able to compare various runs using different type waves including plunging breakers. Figure (25) shows run number two and three from this experiment graphed together with wave number one and three from Fig. (24) in a dimensionless form. Figure (25) indicates that the two experiments results were very similar in both shape and magnitude. The maximum dimensionless pressure occurs at the crest with respect to Kjeldsen's data as is the case with results of this report. Controversy over the exact location of the maximum force is one area in which more research needs to be put forth. Dean, Darlymple and Hudspeth,

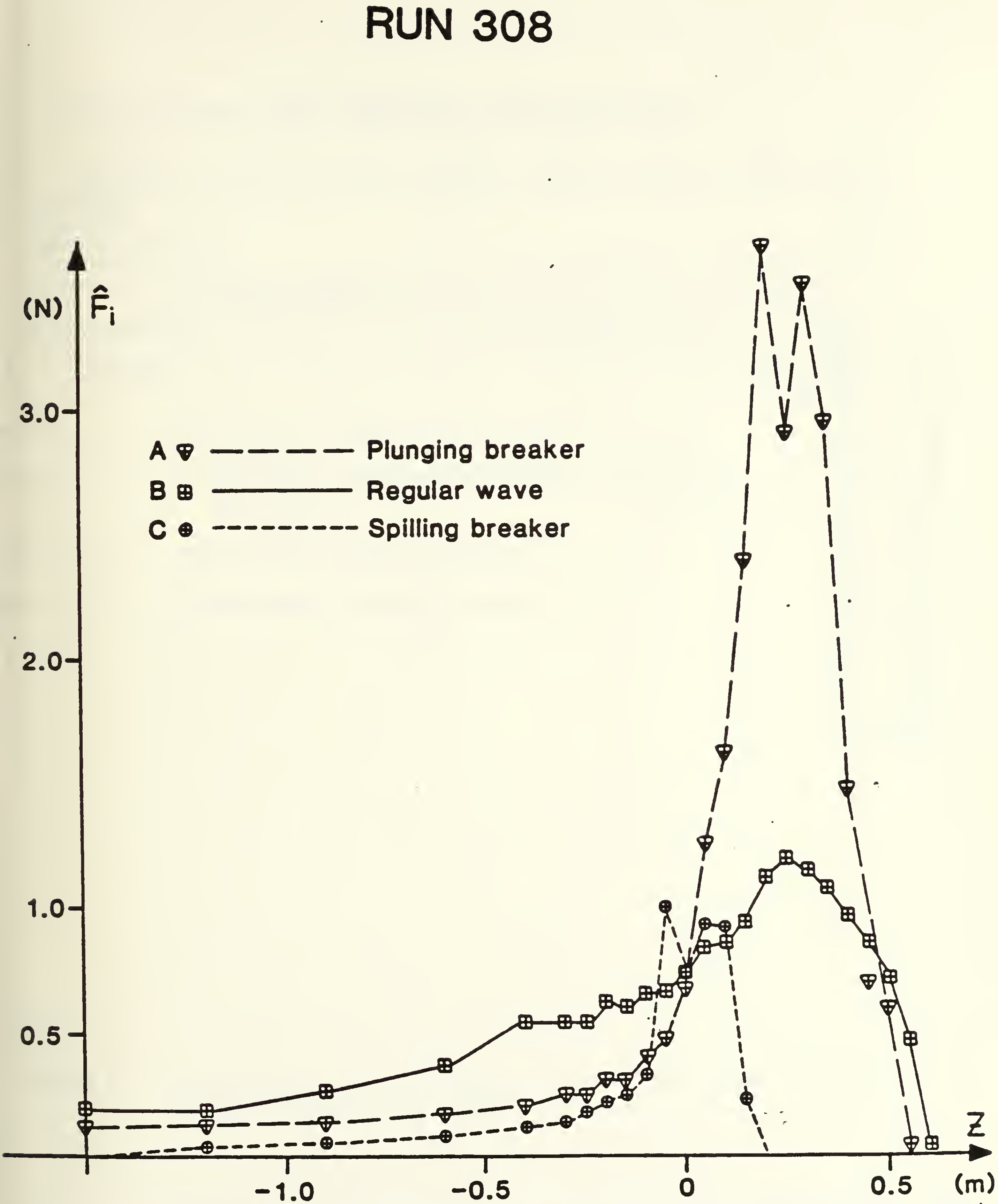


Figure 23. Vertical Force Distribution of Three Different Waves (Kjelsen et al. 1985)

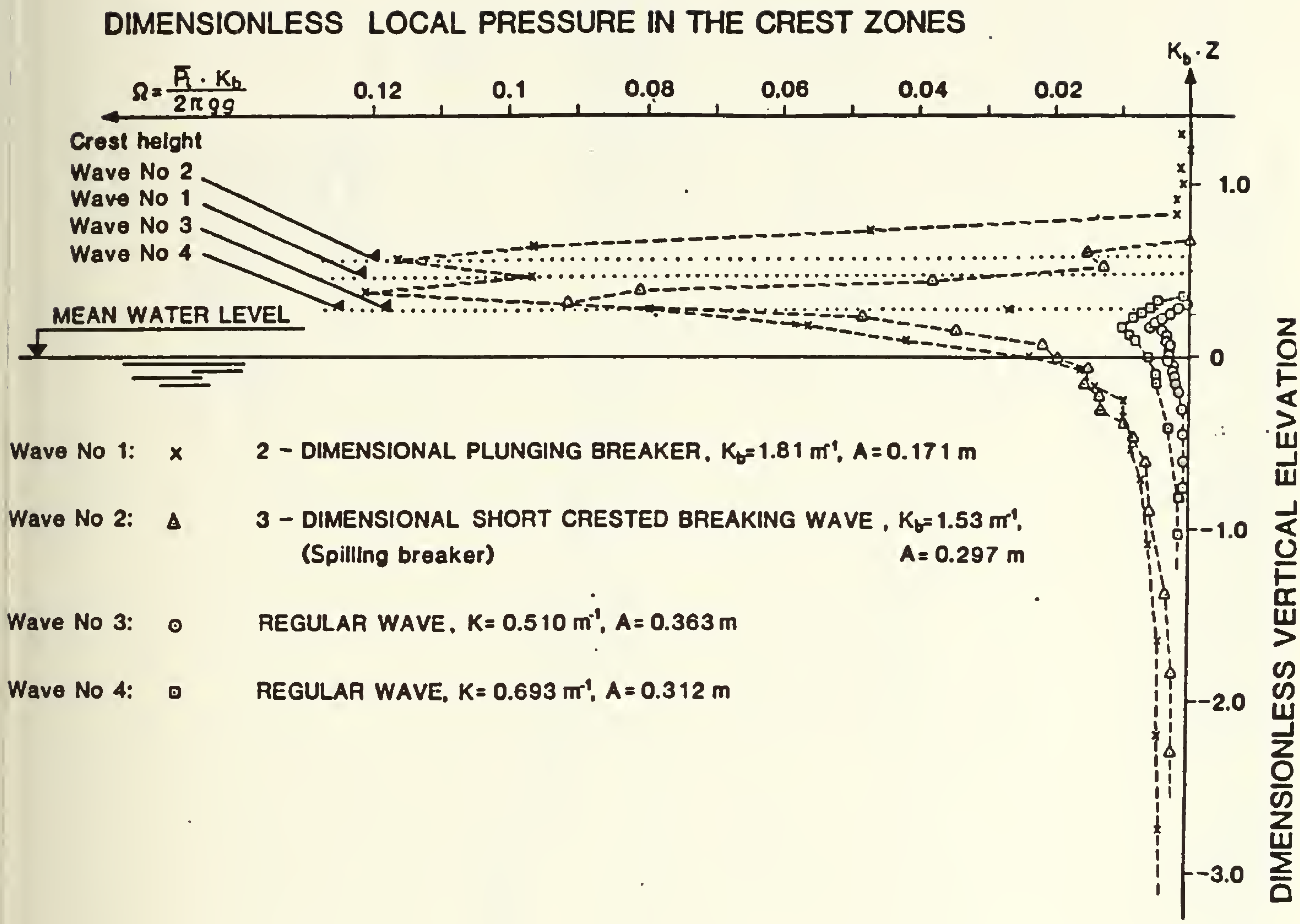


Figure 24. Dimensionless Vertical Pressure Distribution of Four Different Waves (Kjeldsen et al. 1985)

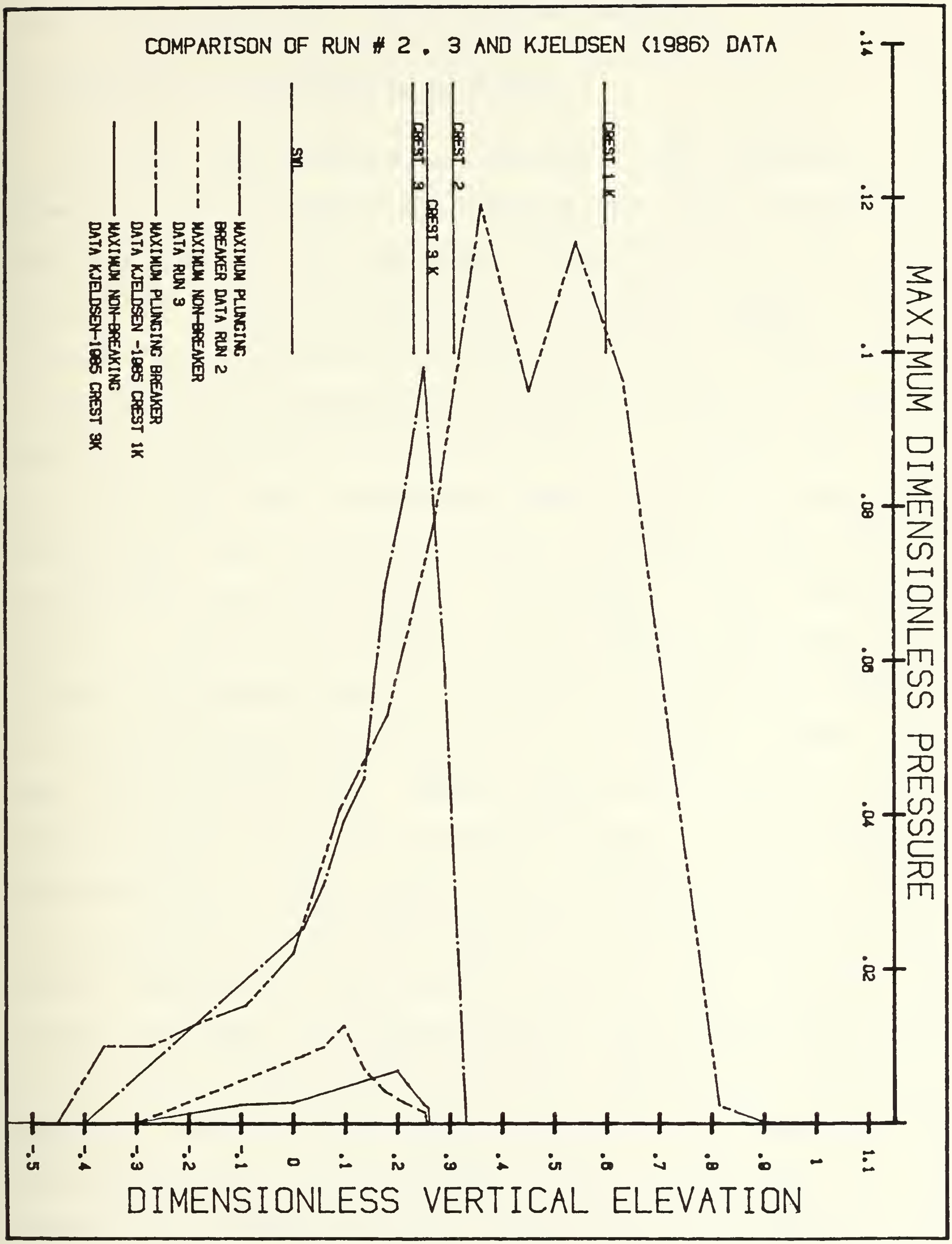


Figure 25. Comparison of Run # 2 and Run # 3 with Kjeldsen et al. (1985) Data of Figure 24.

(1981), suggested the maximum wave force occurs well below the crest due to wave runup and free surface effects.

6.4 Analysis of Non-Breaking Wave Data

As with the breaking wave portion of this experiment two seperate runs to measure non-breaking wave force distribution were performed. This data was desired to compare the force distribution of both breaking and non-breaking waves. It was interesting to observe not only the difference in magnitude of force between the non-breaking and breaking waves but also the difference in vertical force distribution. As shown in Fig. (26) and Fig. (27) the maximum non-breaking vertical wave force distribution had a somewhat different distribution than that of the breaking wave data in Fig. (17) and Fig. (18). The maximum force of the plunging breaker occured closer to the crest than did the non-breaking data. It can also be seen that the magnitude of force is considerably greater in the plunging breaker wave data than non-breaking. Results indicate the plunging breaker force to be ten times the non-breaking force. Data obtained by Kjeldsen et al. (1985), agrees with the above findings. Results of their data indicated that the plunging wave force to be ten to twelve times greater than the non-breaking force. Figures (28) through (31) show both maximum breaking and maximum non-breaking of the four test runs data graphed together for comparison purposes. Graphs of the maximum non-dimensional pressure for the non-breaking wave data are shown in Fig. (32), and Fig.(33). Comparison of both the breaking wave and non-breaking wave non-dimensional pressure data as tabulated in Table I-C through Table

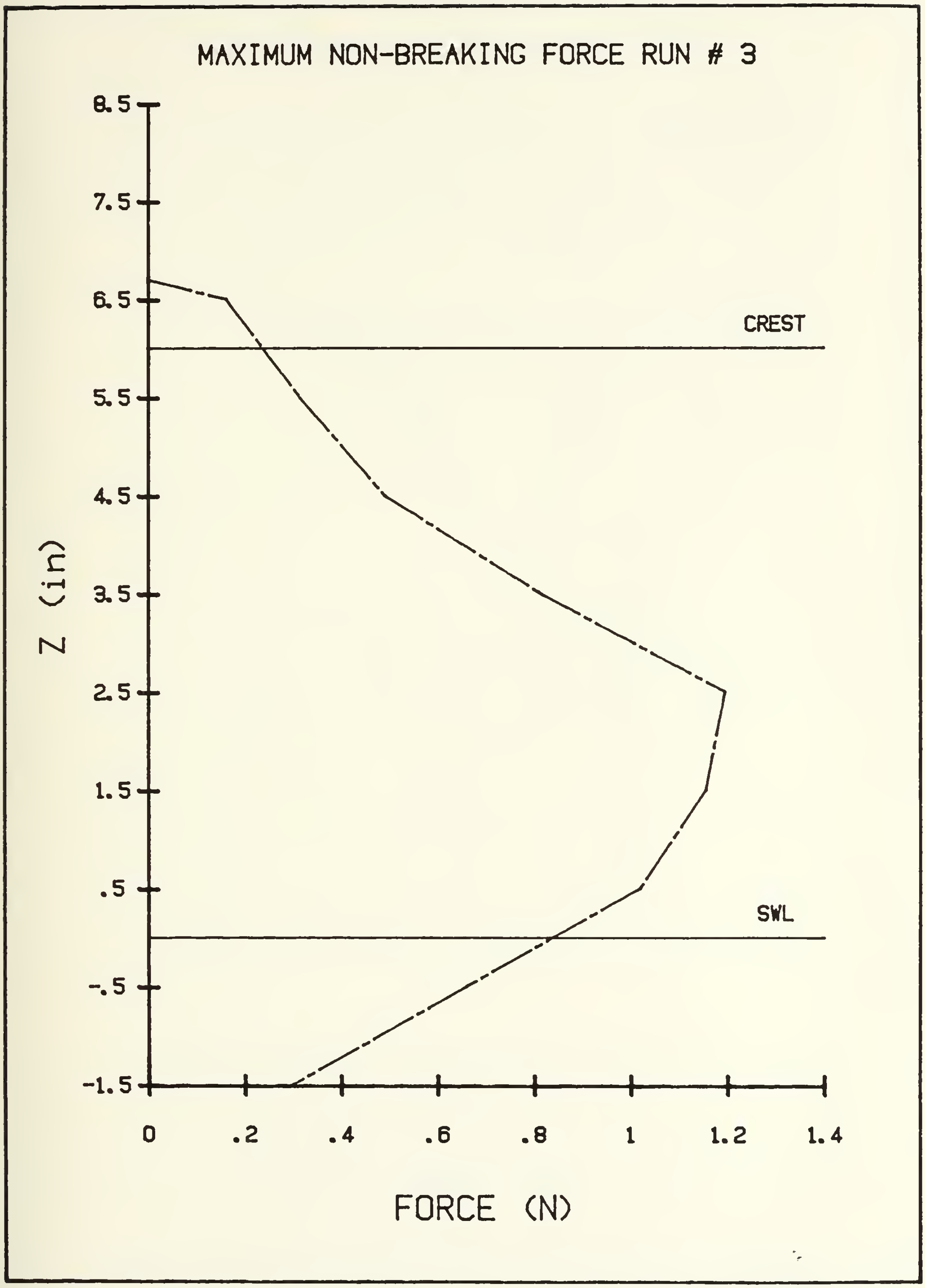


Figure 26. Maximum Vertical Force Distribution of Non-Breaking Wave Run # 3.

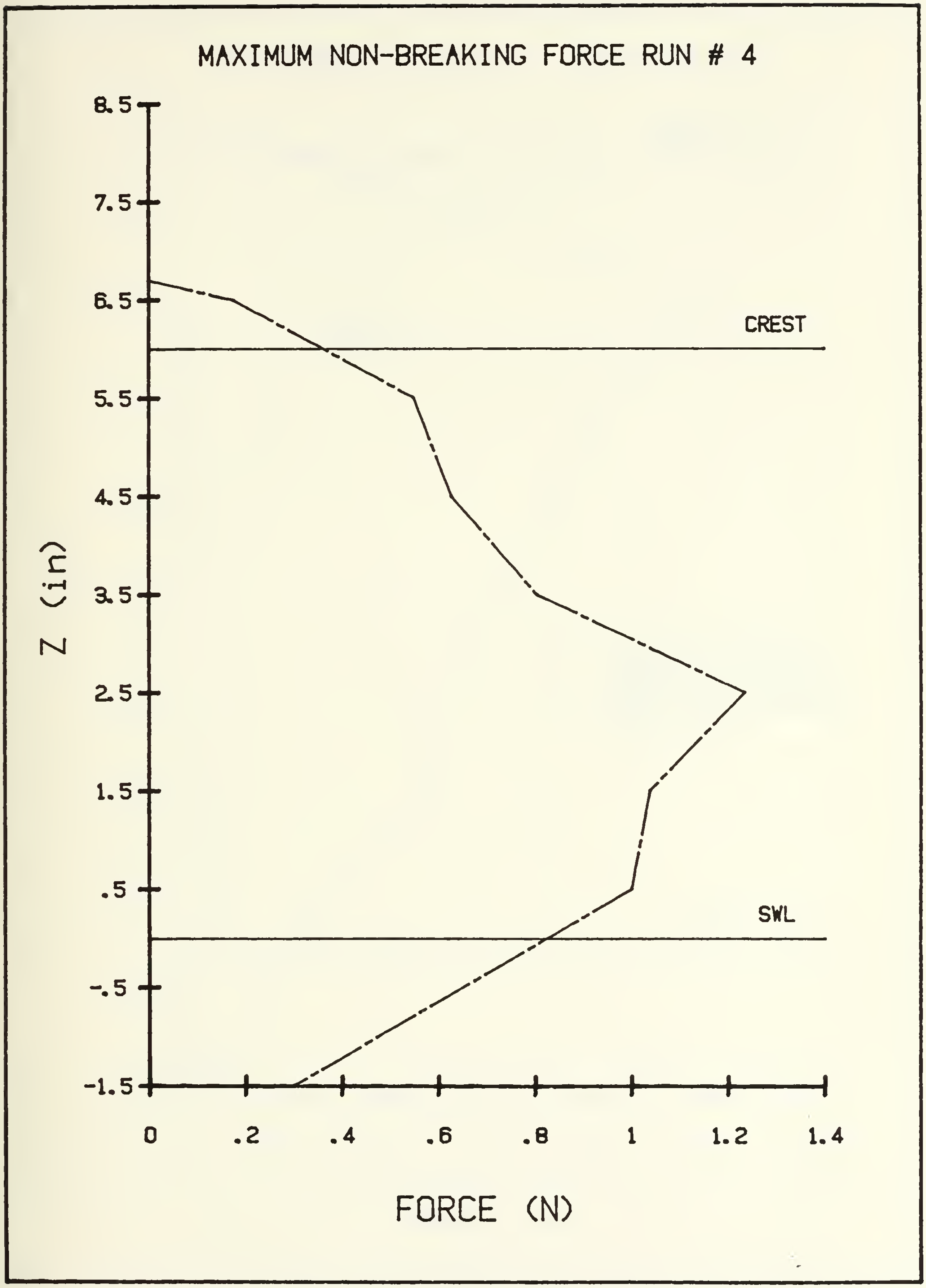


Figure 27. Maximum Vertical Force Distribution of Non-Breaking Wave Run # 4.

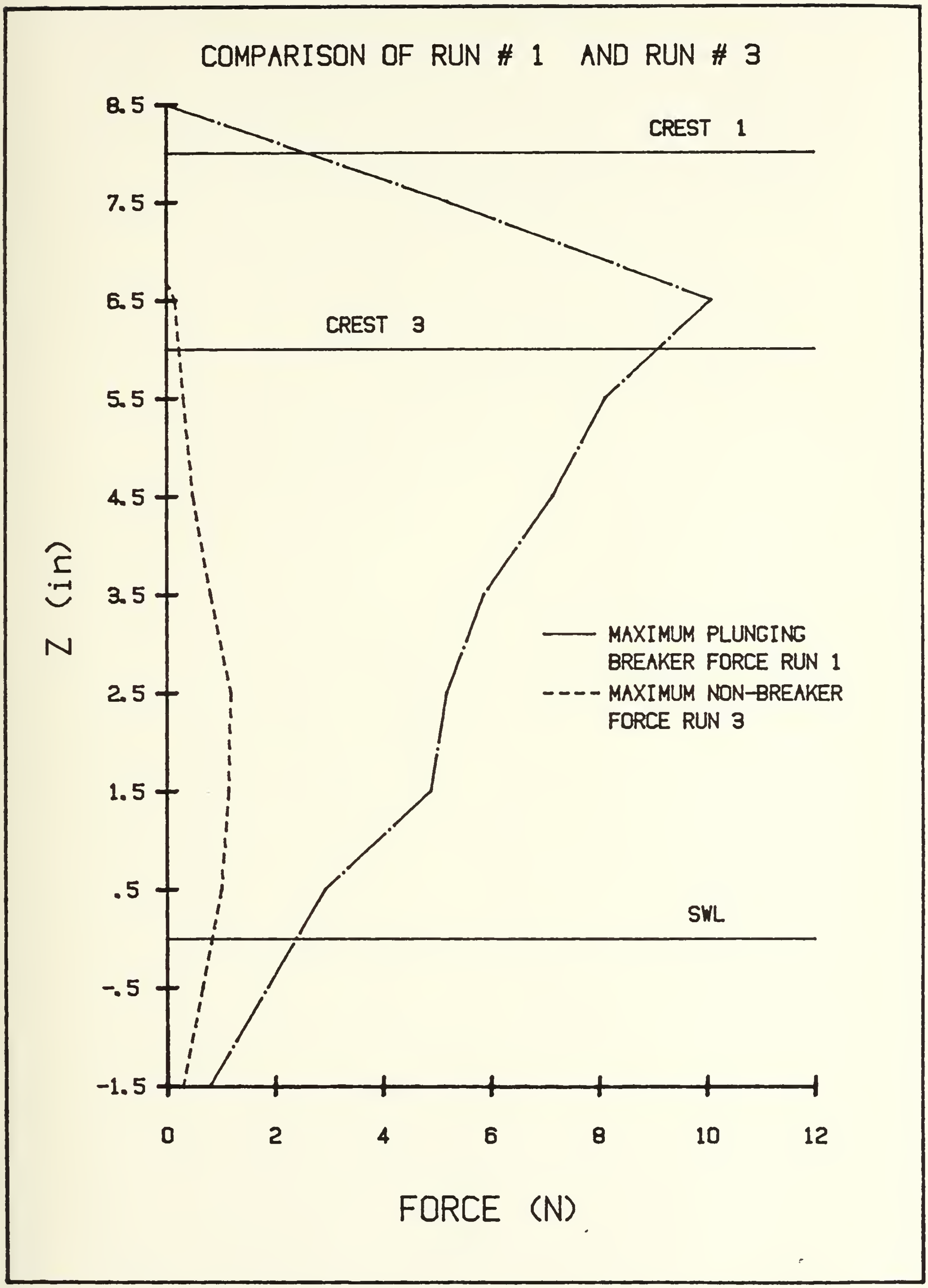


Figure 28. Maximum Vertical Force Distribution of Plunging Wave and Non-breaking Wave Data Run # 1 and Run # 3

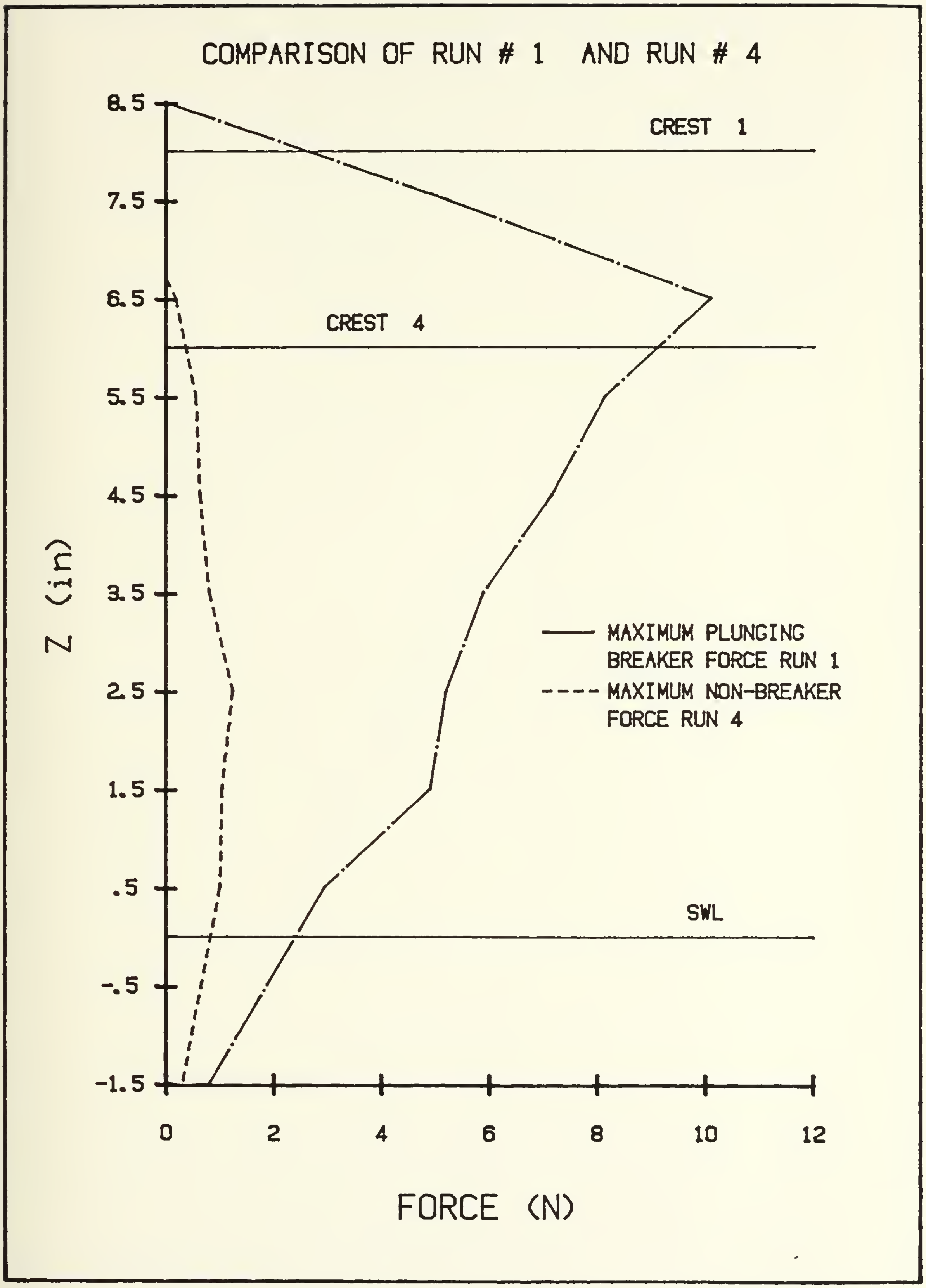


Figure 29. Maximum Vertical Force Distribution of Plunging Wave and Non-Breaking Wave Data Run # 1 and Run # 4.

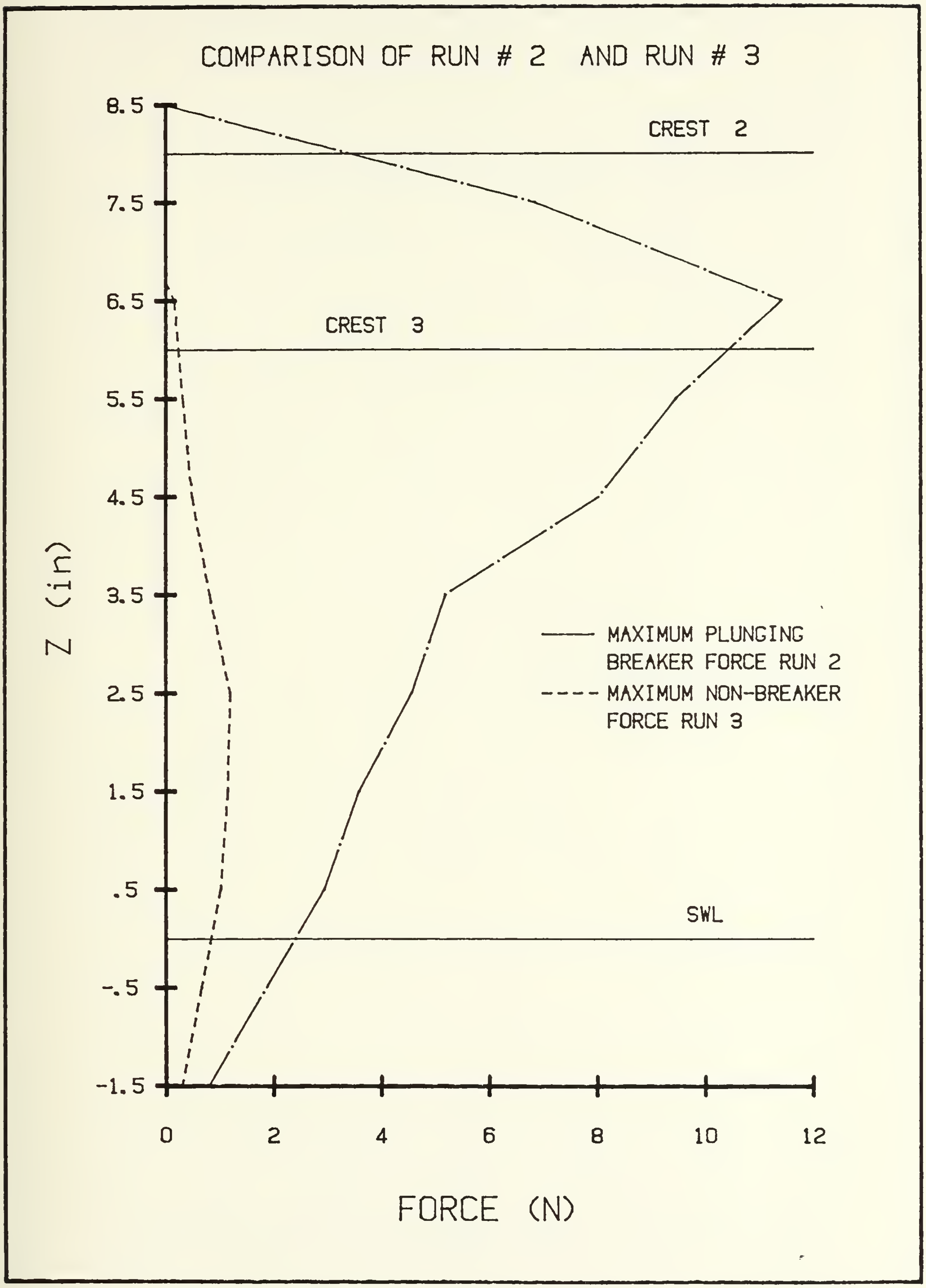


Figure 30. Maximum Vertical Force Distribution of Plunging Wave and Non-Breaking Wave Data Run # 2 and Run # 3.

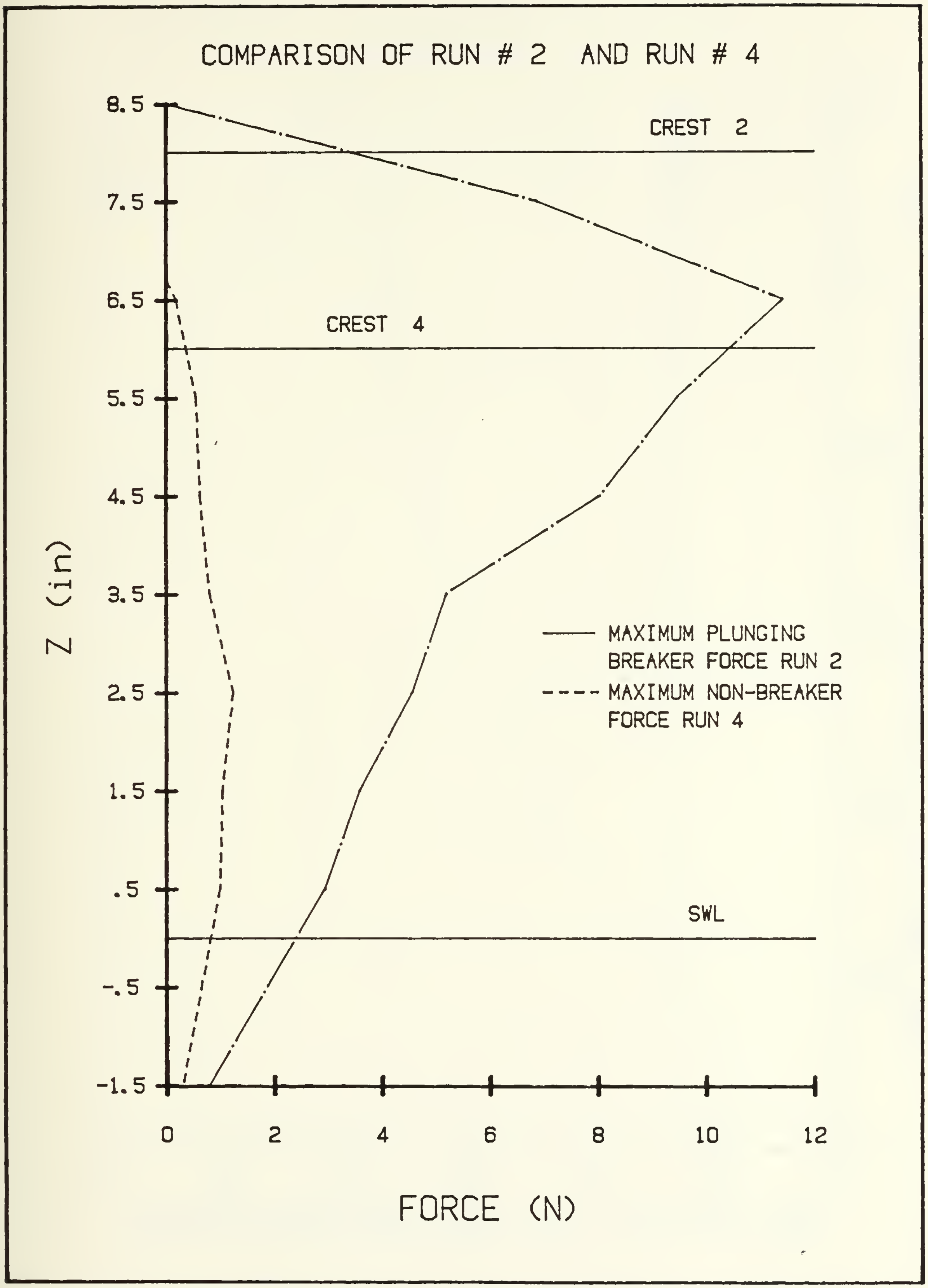


Figure 31. Maximum Vertical Force Distribution of Plunging Wave and Non-Breaking Wave Data Run # 2 and Run # 4.

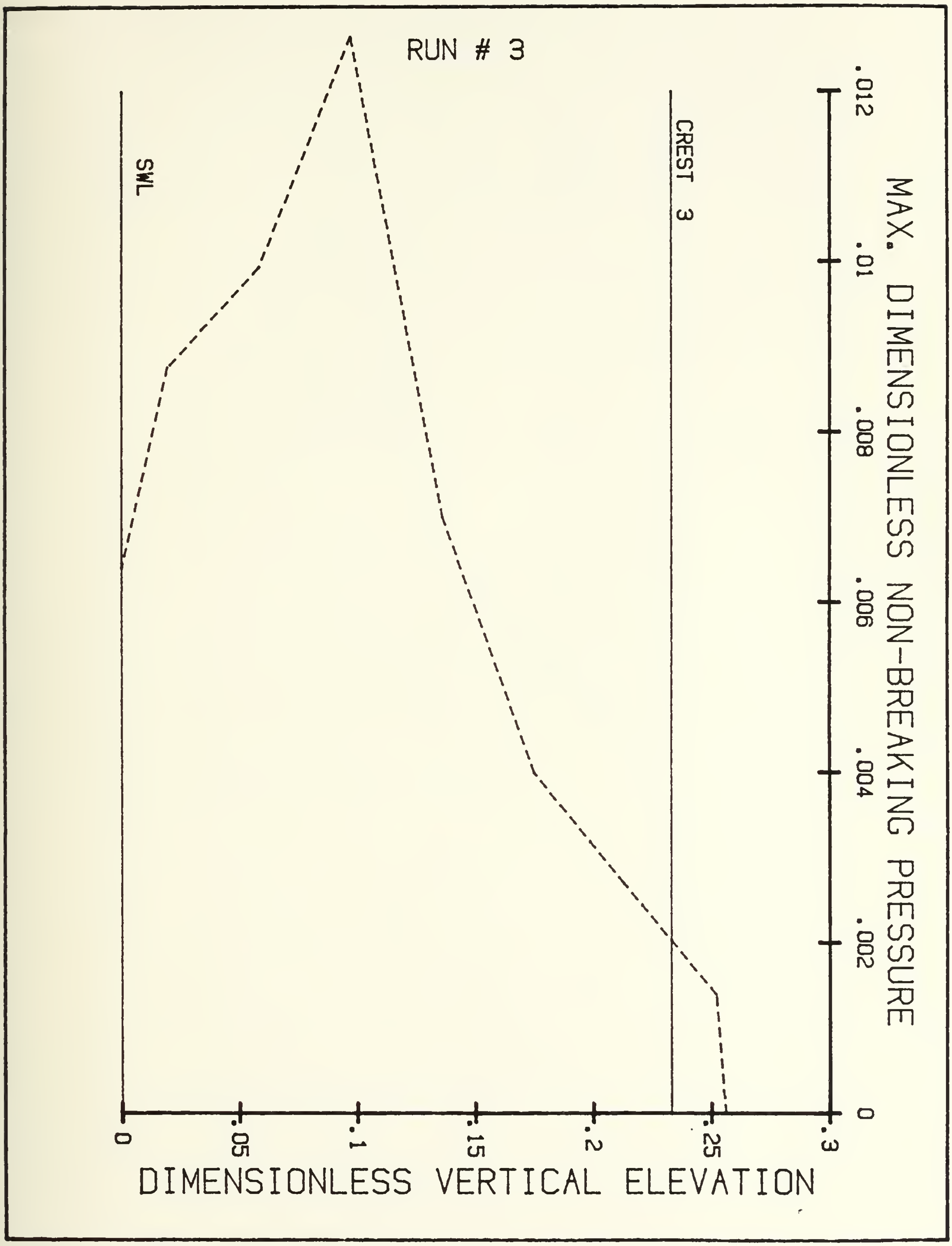


Figure 32. Maximum Vertical Dimensionless Non-Breaking Pressure Distribution Run # 3.

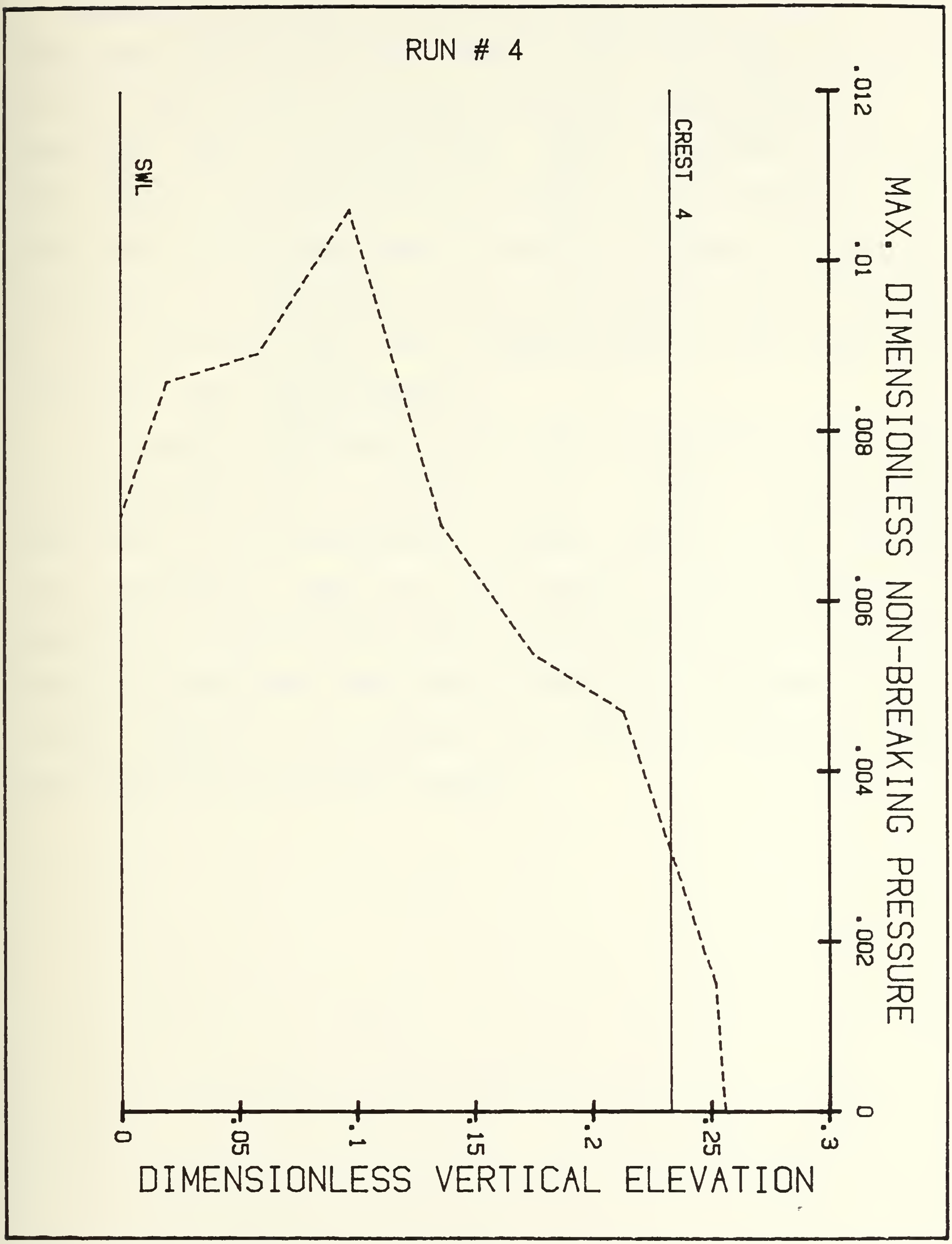


Figure 33. Maximum Vertical Dimensionless Non-Breaking Pressure Distribution Run # 4.

I-F of Appendix II are shown in Figures (34 - 37).

Comparison of the non-breaking wave force data of this experiment as shown in Fig. (26) and Fig (27) with that of Dean et al. (1985) shown in Fig.(38) indicates good agreement in the range from SWL to the wave crest. Little comparison can be made with regards to magnitude of force due to the different areas over which the force acted in the two different experiments. Figure (25) does show dimensionless non-breaking data of Kjeldsen et al. (1985) and data from run number three of this report and once again shows good agreement.

In summary the breaking wave data collected in this study agreed well with that of Kjeldsen et al. (1985). The shape and magnitude of the non-dimensional pressure data for both breaking and non-breaking waves are very similar. The difference in magnitude of force between breaking and non-breaking data of this report corroborated with similar findings of Kjeldsen et al. (1985). Similarity was noted in the position of maximum impact force being at or near the surface.

Figure 34. Comparison of Maximum Vertical Dimensionless Pressure Distribution Run # 1 and Run # 3.

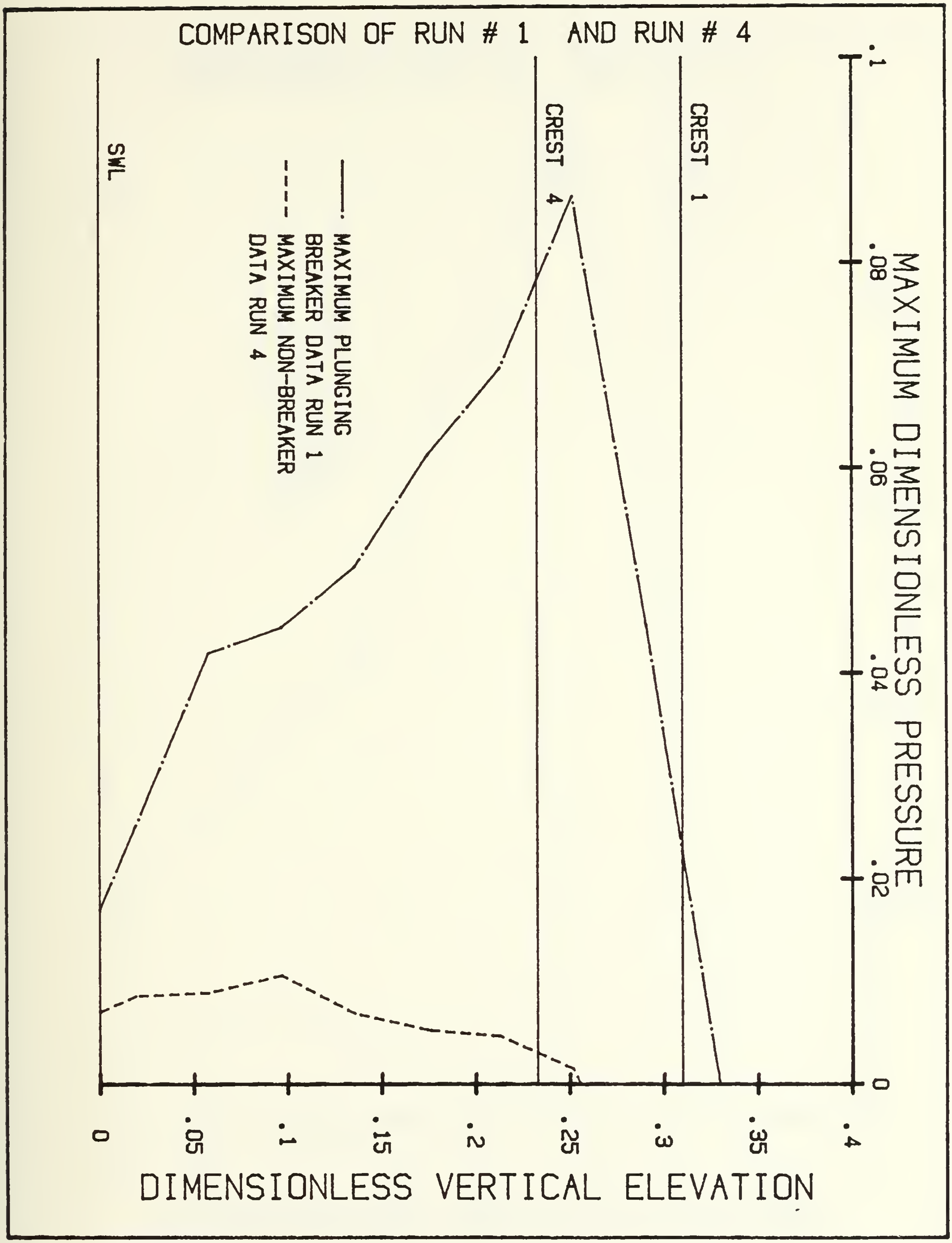


Figure 35. Comparison of Maximum Vertical Dimensionless Pressure Distribution Run # 1 and Run # 4.

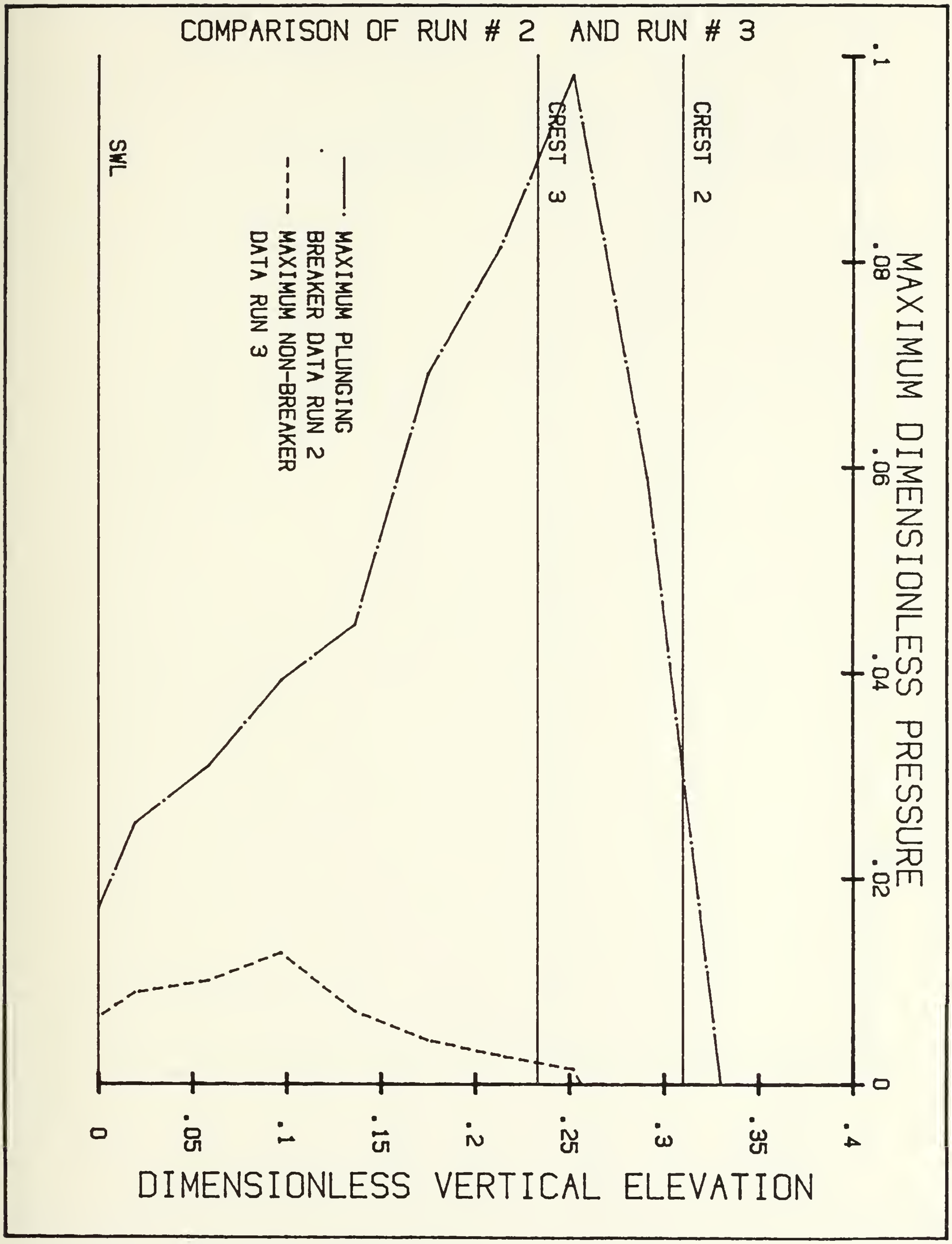


Figure 36. Comparison of Maximum Vertical Dimensionless Pressure Distribution Run # 2 and Run # 3.

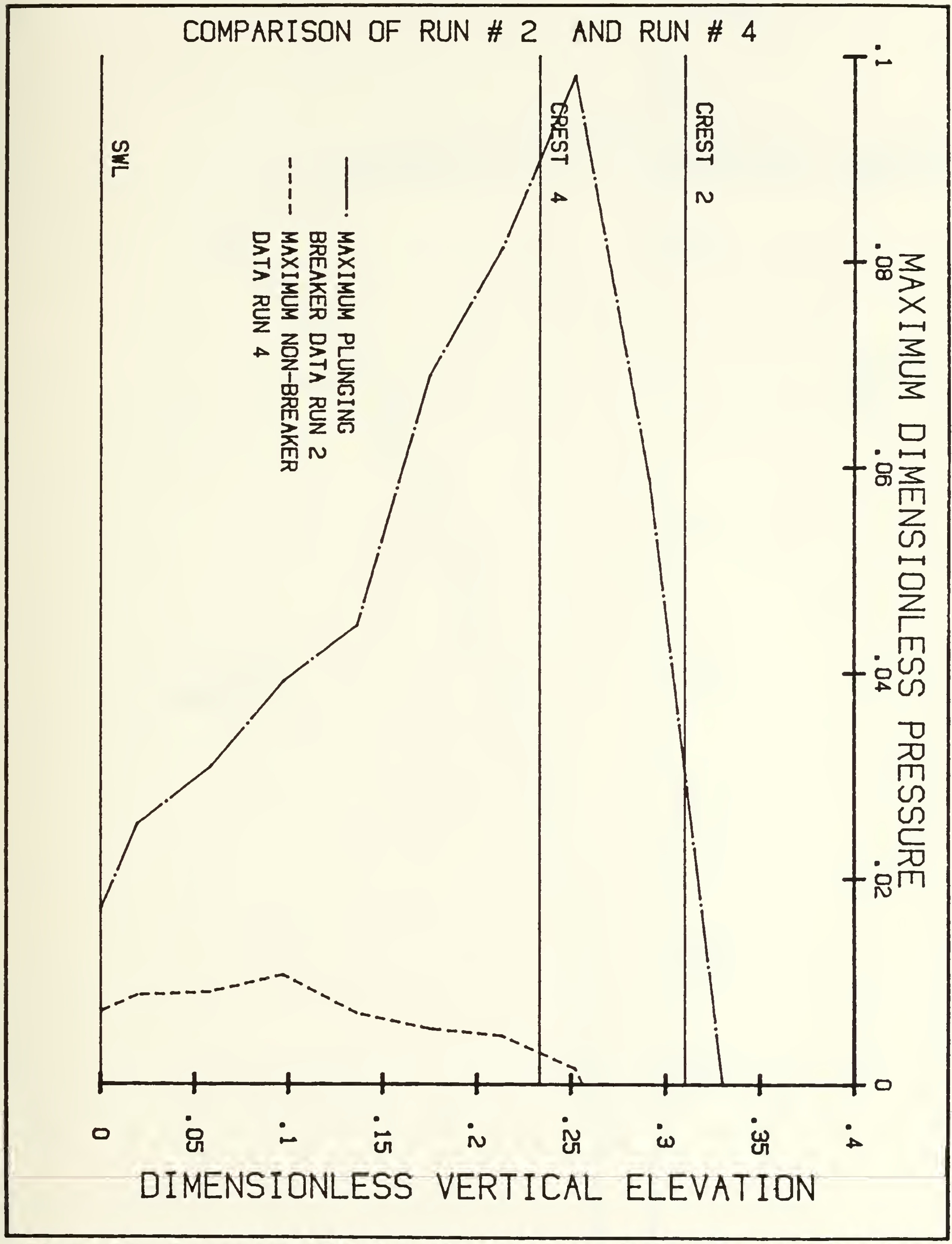


Figure 37. Comparison of Maximum Vertical Dimensionless Pressure Distribution Run # 2 and Run # 4.

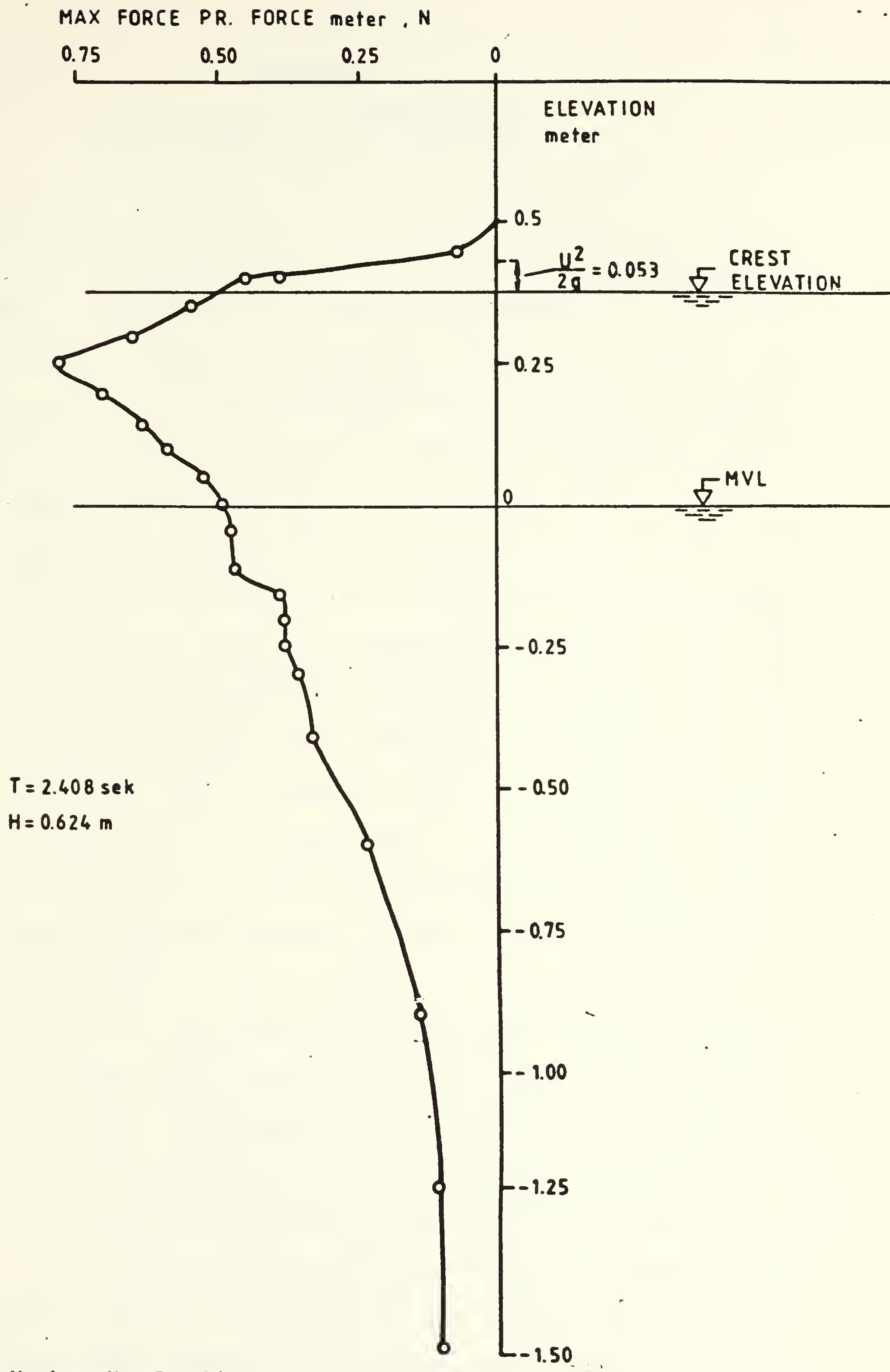


Figure 38. Maximum Non-Breaking Force Distribution
Dean et al. (1985).

CHAPTER 7

CONCLUSIONS AND RECOMMENDATION

7.1 Conclusions

The two major objectives of this report were to design a force measuring device which would be useful in analyzing plunging breaker forces and secondly to use this device and record if possible the force distribution of a plunging breaker in a laboratory wave tank. Both of these objectives have been meet with some success.

The design of the device was unique in that it was to measure not only force but also the directionality of the force. Unfortunately due to lack of machining tolerances in the construction of the device the directionality aspect of the experiment was not achieved. The capability to measure force was successful and the data compared well with other similar experiments conducted in the past. Two distinct force measurements were observed specifically the sudden impact force of short duration and the secondary longer duration force as the wave struck the pile.

Data obtained from use of the above device yielded considerable insight into the wave force profiles of the plunging breaker and the non-breaking wave prior to shoaling. The reduction in magnitude of force of the non-breaking wave in comparison to the breaking wave was significant. Thus it is essential in the design of coastal structures to closely study the structures location in relation to the breaker zone. It was also noticed that the maximum force of the plunging breaker

occured closer to the wave crest than did the maximum force of the non-breaker.

7.2 Recommendations Concerning Laboratory Experiment

As with any endeavor there is always room for improvement and knowledge learned from ones mistakes. Several suggestions are forwarded to help those who may wish to continue in this line of investigation.

1. The force measuring device needs to be machined and constructed to much closer tolerances than was possible with this proto-type. Rivets were used to fasten the flex members to both the PVC collar and the electrical conduit support. A better method of attachment should be considered. One possible suggestion is the use of a high stregth expoxy glue instead of a single rivet. This should ensure complete bonding and secure attachment.

2. The positioning of the flex members at 120 degree segments is a good idea but extreme care must be exercised in the proper and accurate placement of the flex members. The slightest error in placement creates significant calibration problems.

3. Reflection within the wave tank greatly affected the wave break point. More consistent readings could be obtained if the sloping bottom were moved forward in the tank allowing for a longer runup zone and greater wave energy decay.

4. Smaller incremental changes in the vertical movement of the force measuring device should produce a more accurate force distribution. Further more if the force measuring device were not as wide, sensing a smaller portion of the vertical wave column a better force distribution will be obtained.

5. Better instrumentation in which to collect the data is essential. Items such as a high speed movie camera and digital data acquisition are essential. For optimum results some method of simultaneously recording both a visual film record and force data on the same time record would prove to be invaluable and needs to be seriously investigated.

7.3 Recommendations for Possible Field Study

Should one desire to scale up this laboratory force measuring device for possible field usage, several factors should be taken into consideration concerning both the device and experimental apparatus.

1. The design field gauge must be capable of withstanding wave forces to be encountered at the experimental site. Thus some knowledge of a design wave must be known. From preliminary results of this experiment one can expect the breaking wave force to be approximately ten times that of the deep water non-breaking wave. The non-breaking wave force may be calculated from Morison's equation and an appropriate wave theory.

2. As with the laboratory gauge proper selection of materials is critical. Corrosion will need to be accounted for along with proper protective coatings to withstand the extreme environmental conditions.

3. Consideration should be given concerning the possibility of using several wave force measuring devices instead of just one. By using numerous devices one can forego the cumbersome task of raising and lowering the device inorder to obtain a vertical force distribution.

4. Adequate data collection equipment is essential. The equipment should be portable if possible. Due to the variable nature of field conditions the equipment should have a wide range of sensitivity. This would provide greater contingency and a higher success rate of collecting precise data.

REFERENCES

Bagnold, R.A., "Interim Report on Wave Pressure Research", Journal, Instutution of Civil Engineering, London, Vol. 2, June 1938-39, pp. 202-22.

Dean, R.G., Dalrymple R.A., Hudspeth R.T., " Force Coefficients from Wave Projects I and II. Data including free surface effects", Society of Petroleum Engineers Journal. December 1981, pp. 777-786

Dean, R.G., Torum, A., and Kjeldsen, S.P., "Wave Forces on a Pile in the Surface Zone From Wave Crest to the Wave Trough", Royal Norwegian Council for Scientific and Indurstral Research (NTNF), Research Project, Programme for Marine Structures, Report No. 1.7, April 1985.

De Rouville, A., Besson, P., and Petry, P., "Etat actual des e'tudes internationales sur les efforts dus aux lames", (Development of International Studies on Wave Force), Annales des Ponts et Chaussee's, Vol. 108, No. 7, July 1938, pp. 5 - 113, translated by U.S. Army Engineer Waterways Experiment Station Research Center, Vicksburg, Miss., Tr. No. 40-13, May 1940.

Gaillard, D.D., "Wave Action in Relation to Engineering Structures", The Engineer School, 1904, U.S. Army Corps of Engineers, Ft. Belvoir, Va.

Garcia, W.J., "An Experimental Study of Breaking-Wave Pressures", Research Report H-68-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Sept. 1968.

Goda, Y., Haranaka, S., and Kitahata, M., " Study of Impulsive Breaking Wave Forces on Piles", Report Port and Harbor Research Institute, Ministry of Transport, Japan, Vol.5, No.6, 1966, (in Japanese)

Goda, Y., "Wave Forces on Circular Cylinders Erected on Reefs". Coastal Engineering in Japan, Vol. 16, 1973.

Hall, M.A., "Laboratory Study of Breaking Wave Forces on Piles", Beach Erosion Board, Technical Memorandum, No. 106, August 1958.

Kjeldsen, S.P., and Akre, A.R., "Wave Forces on Vertical Piles Near the Free Surface Caused by Two Dimensional Breaking Waves" Royal Norwegian Council for Scientific and Industrial Research (NTNF), Research Project, Programme for Marine Structures, Report No. 1.10, November 1985.

Larras, J., "Recherches experimentales sur le deferlement des lames", (Experimental Investigations on the breaking of the Waves), Annales Ponts et chausse'es, Vol. 122, Series 8, Sept.-Oct. 1952, pp. 525-542.

Miller, R.L., Leverette, S., O'Sullivan, J., Tochko, J., and Theiriault, K., "Field Measurements of Impact Pressures in Surf", Proceedings 14th Coastal Engineering Conference, Copenhagen, 1974, Vol.3, pp.1761-1777.

Morison, J.R., "The Design of Piling", Proceedings 1st Conference On Coastal Engineering", Long Beach CA. ,October 1950, Vol. 1, pp. 254-258.

Morison, J.R., Johnson, J.W., and O'Brien, M.P., "Experimental Studies of Forces on Piles", Proceedings 4th Conference on Coastal Engineering, Chicago IL., 1953, Vol. 4, pp. 340-370.

Morison, J.R., O'Brien, M.P., "The Forces Exerted by Waves on Objects ", Series 3, Issue 310, IER, University Of California, Berkeley,CA., 1950.

Nagai, S., "Shock Pressure Exerted by Breaking Waves on Breakwaters", Transactions, ASCE, June 1960, Paper 3261, pp. 772-809.

Panigrahi, P.R., "Wave Forces on Piles in Surf Zones - A Literature Survey", An Engineering Report, College of Engineering (Ocean Engineering), Texas A&M University, 1985

Priest, M.S., "Shallow Water Wave Action on a Verticle Cylinder", Journal of Waterways and Harbor Division, Proc. of ASCE, May 1962, No. WW2, pp. 1-9.

Reid, R.O., and Bretschnider, L. "Surface Waves and Offshore Structures: The Design Wave in Deep or Shallow Water, Storm Tide and Forces on Verticle Piles and Large Submerged Objects", Texas A&M University, Dept. Of Oceanography, Tech. Report, Oct. 1953.

Snodgrass, F.E., Rice, E.K., and Hall, M., "Wave Forces on Pilings", Montery Field Test, Tech. Report, No. 35-4, Institute of Engineering Research, Univ. of California, Berkley,CA., June 1951.

Wantanabe, A., Horikawa, K., "Breaking Wave Forces on a Large Diameter Cell", Proceedings 14th Coastal Engineering Conference, Cohenhagen, Denmark, 1974, Vol.3, pp. 1741-1760.

Wiegel, R.L., "Forces Induced by Breakers on Piles", Proceedings 18th Coastal Engineering, Conference, Cape Town, South Africa, 1982,Vol. 2 pp.1699-1715.

Wiegel, R.L., Beebe, K.E., and Moon, J., "Ocean Wave Forces on Circular Cylindrical Piles", Journal of the Hydraulic Division, Proceedings, ASCE, Vol. 83, No. H 12, Paper 1199, April 1957.

APPENDIX I

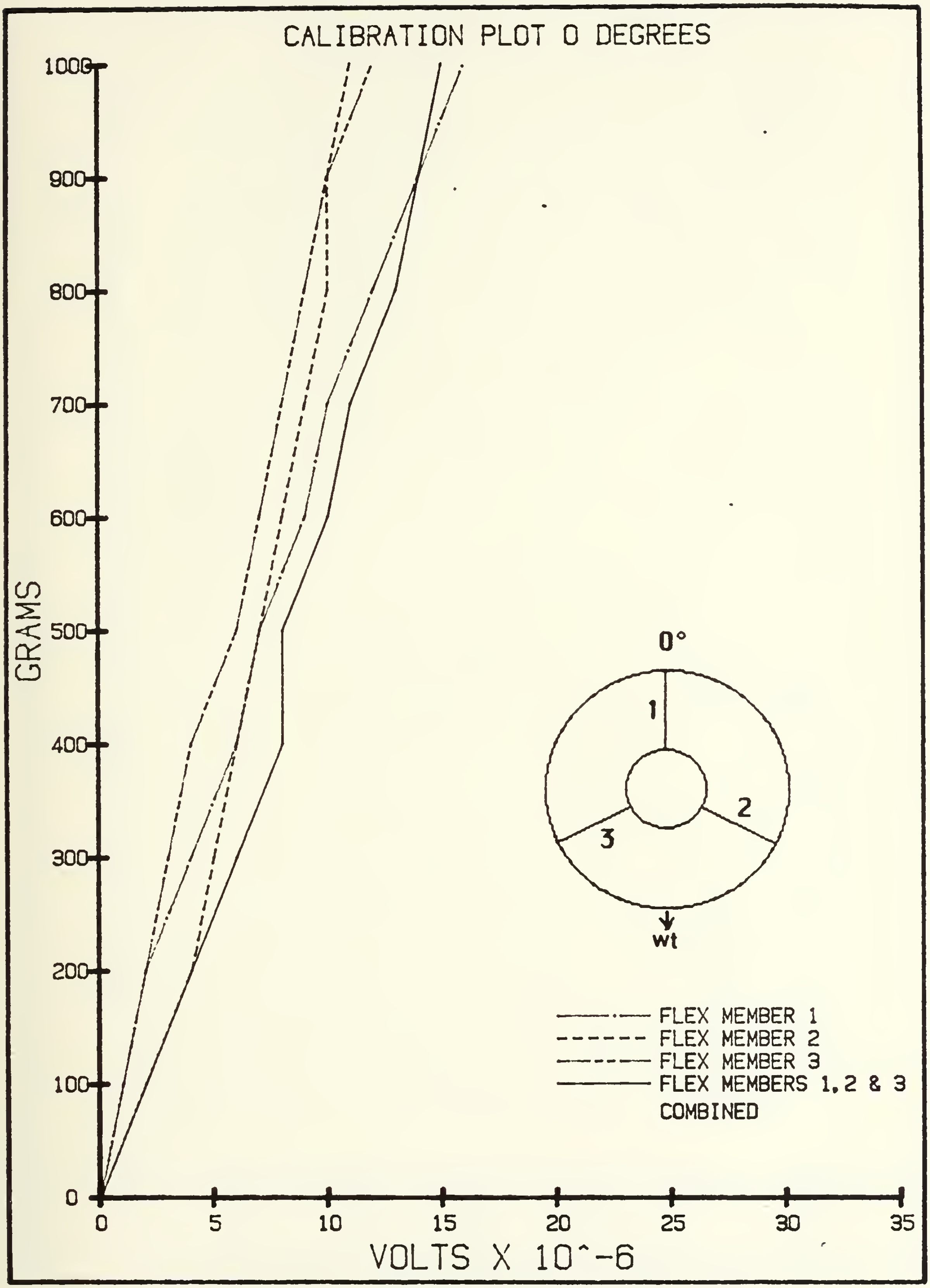


Figure 39. Calibration Plot 0 Degrees Using an HP 3497.

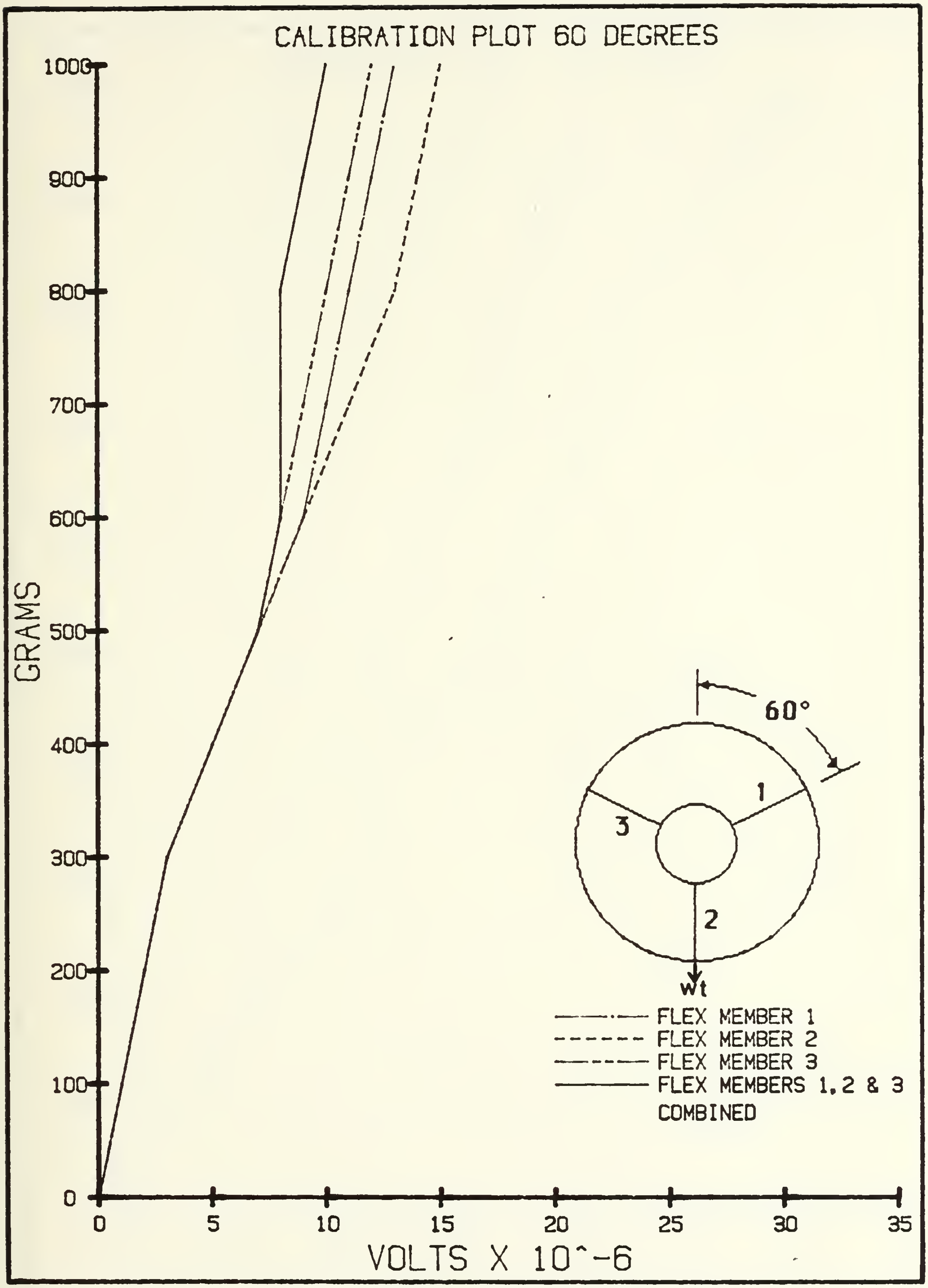


Figure 40. Calibration Plot 60 Degrees Using an HP 3497.

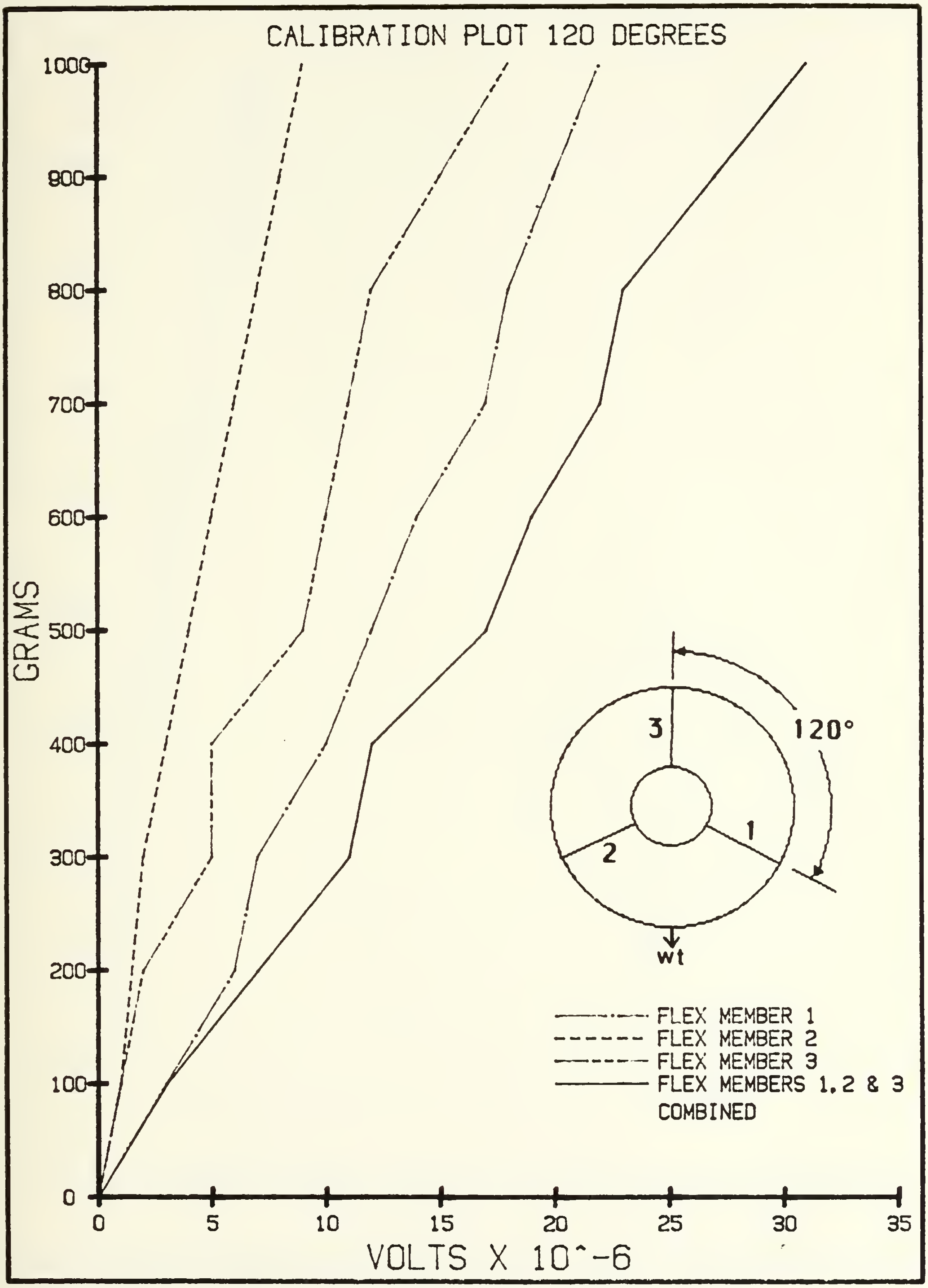


Figure 41. Calibration Plot 120 Degrees Using an Hp 3497.

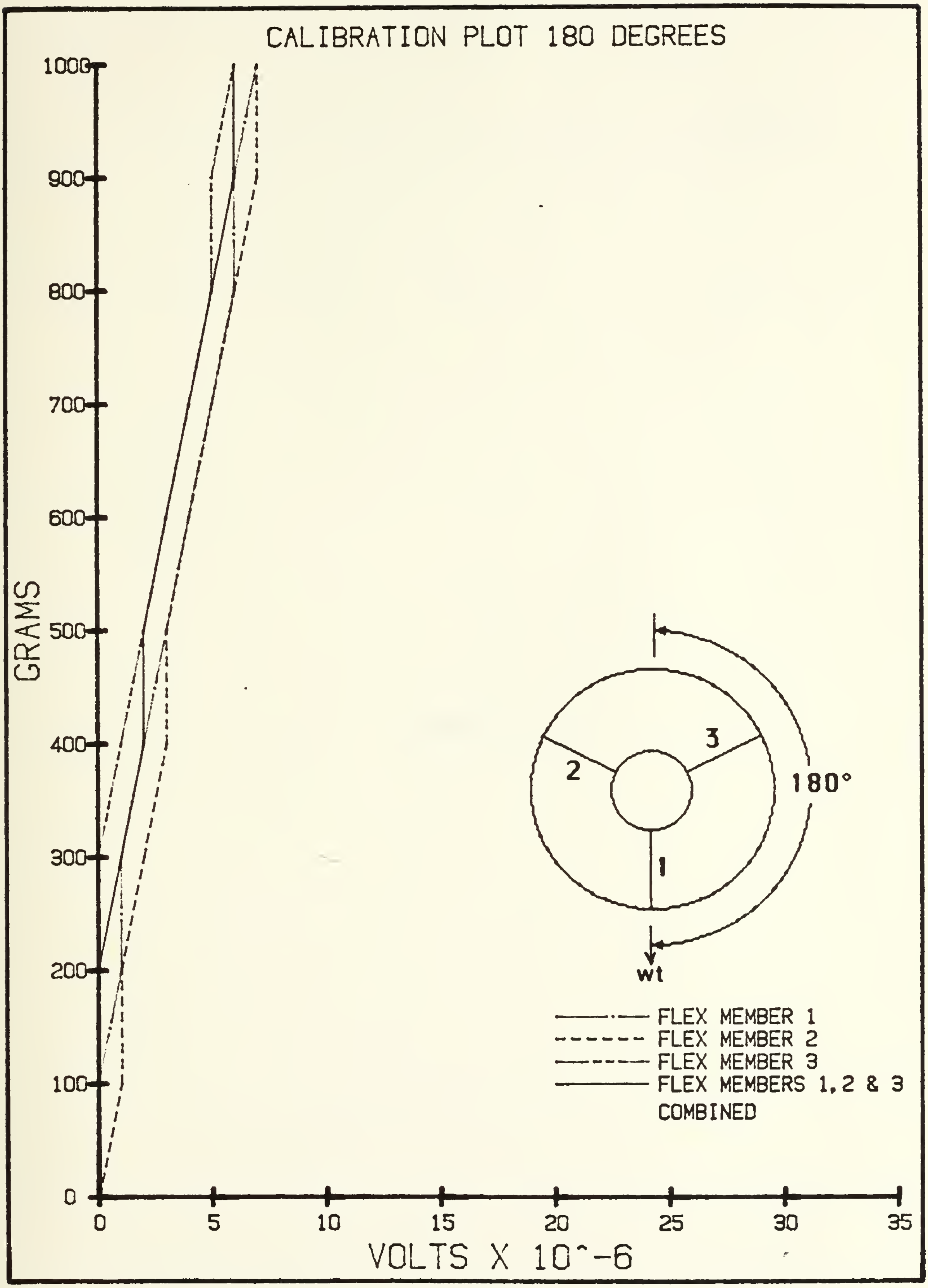


Figure 42. Calibration Plot 180 Degrees Using an HP 3497.

APPENDIX II

TABLE I-A

Maximum Plunging Breaker Force Run #1 and Run #2

	FORCE (N)	
Z (in)	Run #1	Run #2
7.5	5.220	6.860
6.5	10.094	11.426
5.5	8.134	9.467
4.5	7.154	8.036
3.5	5.880	5.194
2.5	5.194	4.566
1.5	4.900	3.586
0.5	2.940	2.940

TABLE I-B

Maximum Non-Breaking Force Run #3 and Run #4

	FORCE (N)	
Z (in)	Run #3	Run #4
6.5	.162	.176
5.5	.314	.548
4.5	.490	.627
3.5	.814	.803
2.5	1.195	1.235
1.5	1.156	1.038
0.5	1.019	.999
-0.5	.666	-

TABLE I-C

Conversion of Maximum Plunging Breaker Force to Dimensionless Pressure

RUN #1

Z (in)	Z (m)	Force (N)	Pressure (N/M)		Kb(Z)
7.5	.190	5.220	1798.00	.044	.291
6.5	.165	10.094	3476.83	.086	.252
5.5	.139	8.134	2801.70	.069	.213
4.5	.114	7.154	2464.15	.061	.175
3.5	.089	5.880	2025.30	.050	.136
2.5	.064	5.194	1789.04	.044	.097
1.5	.038	4.900	1687.77	.042	.058
0.5	.013	2.940	1012.66	.025	.019

1. Pressure = Force / Area ; Pi = F / A ; (Area =.0029m)
2. Wave Number = $Kb = \dfrac{4\ \pi^2}{(g)\ Tzdb}$ Tzdb = 2.63 sec
3. Dimensionless Pressure = $= \dfrac{Pi\ (Kb)}{2\ \pi\ \rho\ g}$
4. Dimensionless Elevation = Kb (Z)

TABLE I-D

Conversion of Maximum Plunging Breaker Force to Dimensionless Pressure

RUN #2

Z (in)	Z (m)	Force (N)	Pressure (N/M)		Kb(Z)
7.5	.190	6.860	2365.51	.058	.291
6.5	.165	11.426	3940.00	.098	.252
5.5	.139	9.467	3264.48	.081	.213
4.5	.114	8.036	2771.03	.068	.175
3.5	.089	5.194	1791.03	.044	.136
2.5	.064	4.566	1574.48	.039	.097
1.5	.038	3.586	1236.55	.030	.058
.5	.013	2.940	1013.79	.025	.019

TABLE I-E

Conversion of Maximum Non-Breaking Force to Dimensionless Pressure

RUN #3

Z (in)	Z (m)	Force (N)	Pressure (N/M)		Kb(Z)
6.5	.165	.162	55.860	.0014	.252
5.5	.139	.314	108.27	.0027	.213
4.5	.114	.490	168.96	.0042	.175
3.5	.089	.813	280.48	.0070	.136
2.5	.064	1.195	412.27	.0126	.097
1.5	.038	1.156	398.63	.0099	.058
.5	.013	1.019	351.44	.0087	.019

TABLE I-F

Conversion of Maximum Non-Breaking Force to Dimensionless Pressure

RUN #4

Z (in)	Z (m)	Force (N)	Pressure (N/M)		Kb(Z)
6.5	.165	.176	60.68	.0015	.252
5.5	.139	.548	189.24	.0047	.213
4.5	.114	.627	216.20	.0053	.174
3.5	.089	.803	276.89	.0068	.136
2.5	.064	1.235	425.86	.0106	.097
1.5	.038	1.038	357.93	.0089	.058
.5	.013	.999	344.68	.0085	.019

APPENDIX III

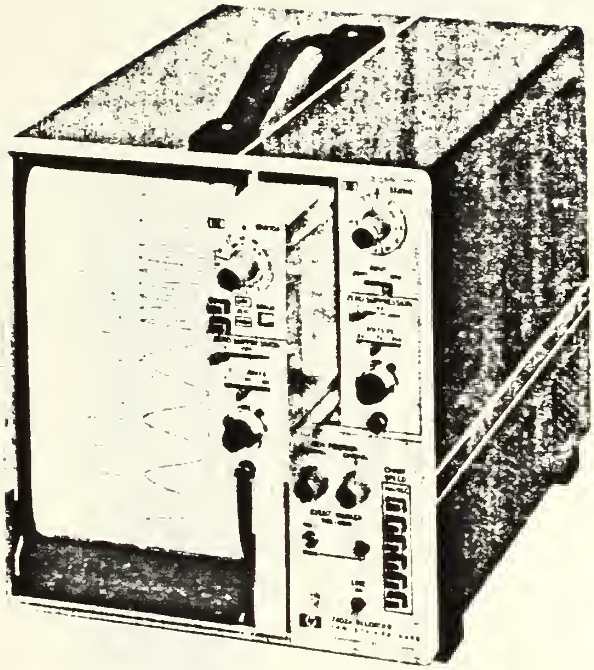


Figure 43. Hewlett Packard 7402A Oscillographic Chart Recorder

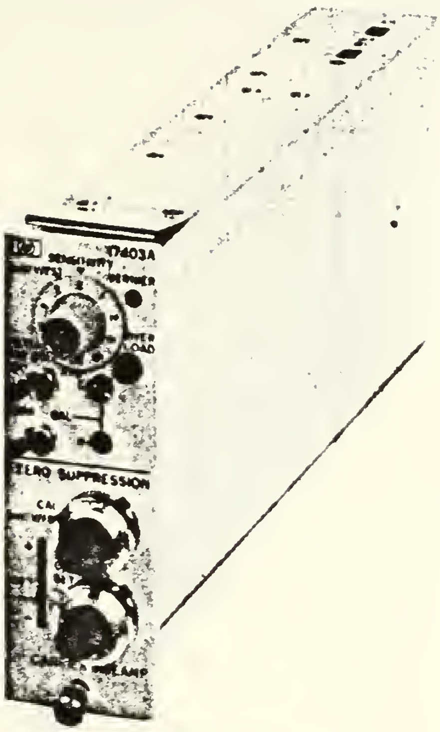


Figure 44. Hewlett Packard 17403A AC Carrier Preamplifier

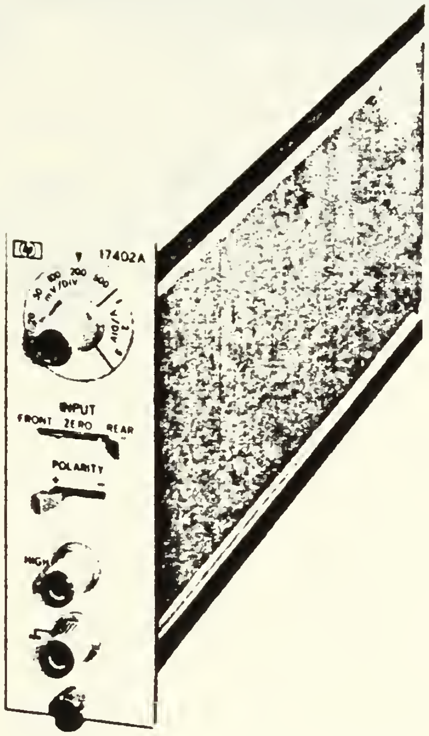


Figure 45. Hewlett Packard 17402A Low-Gain DC Preamplifier

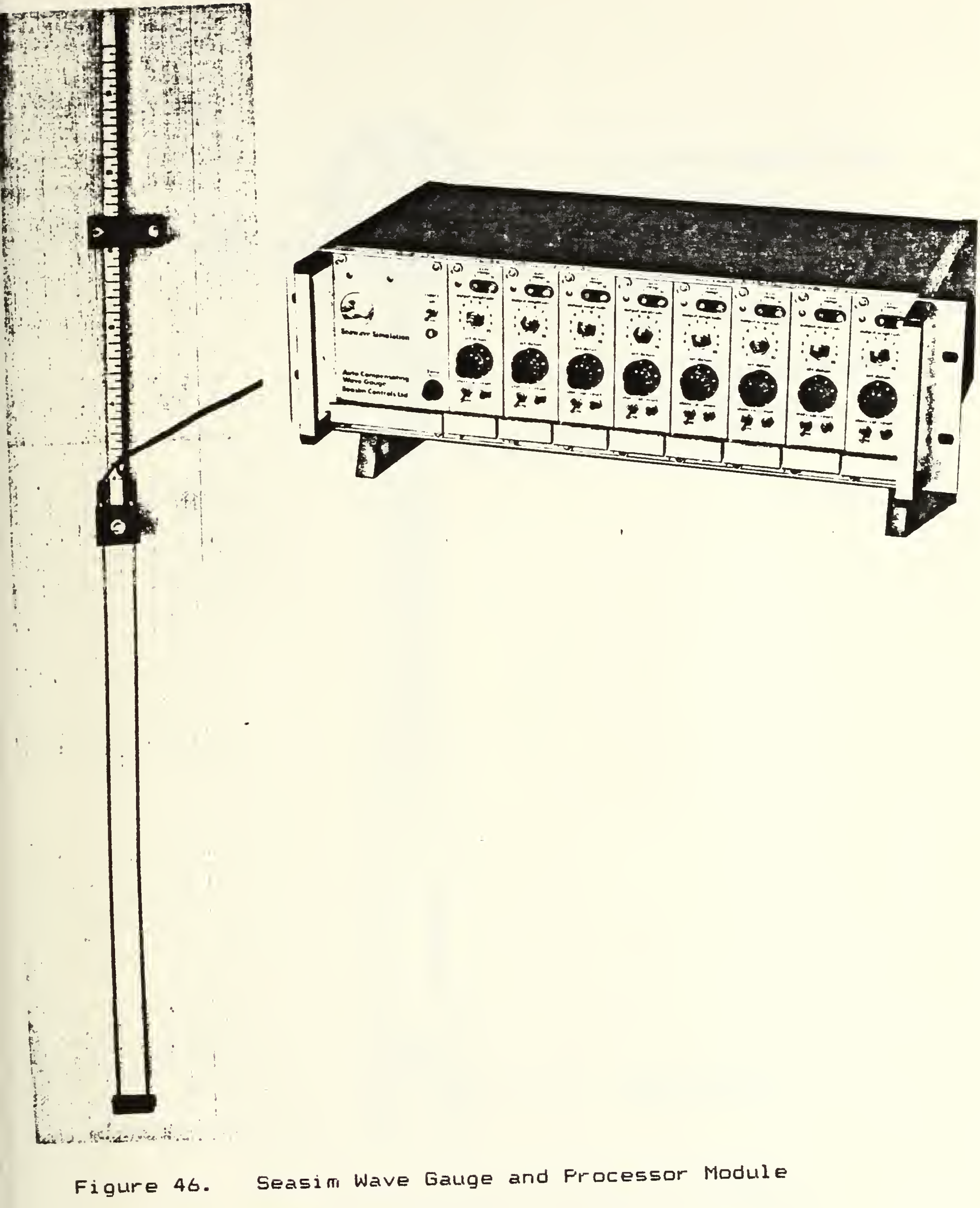


Figure 46. Seasim Wave Gauge and Processor Module

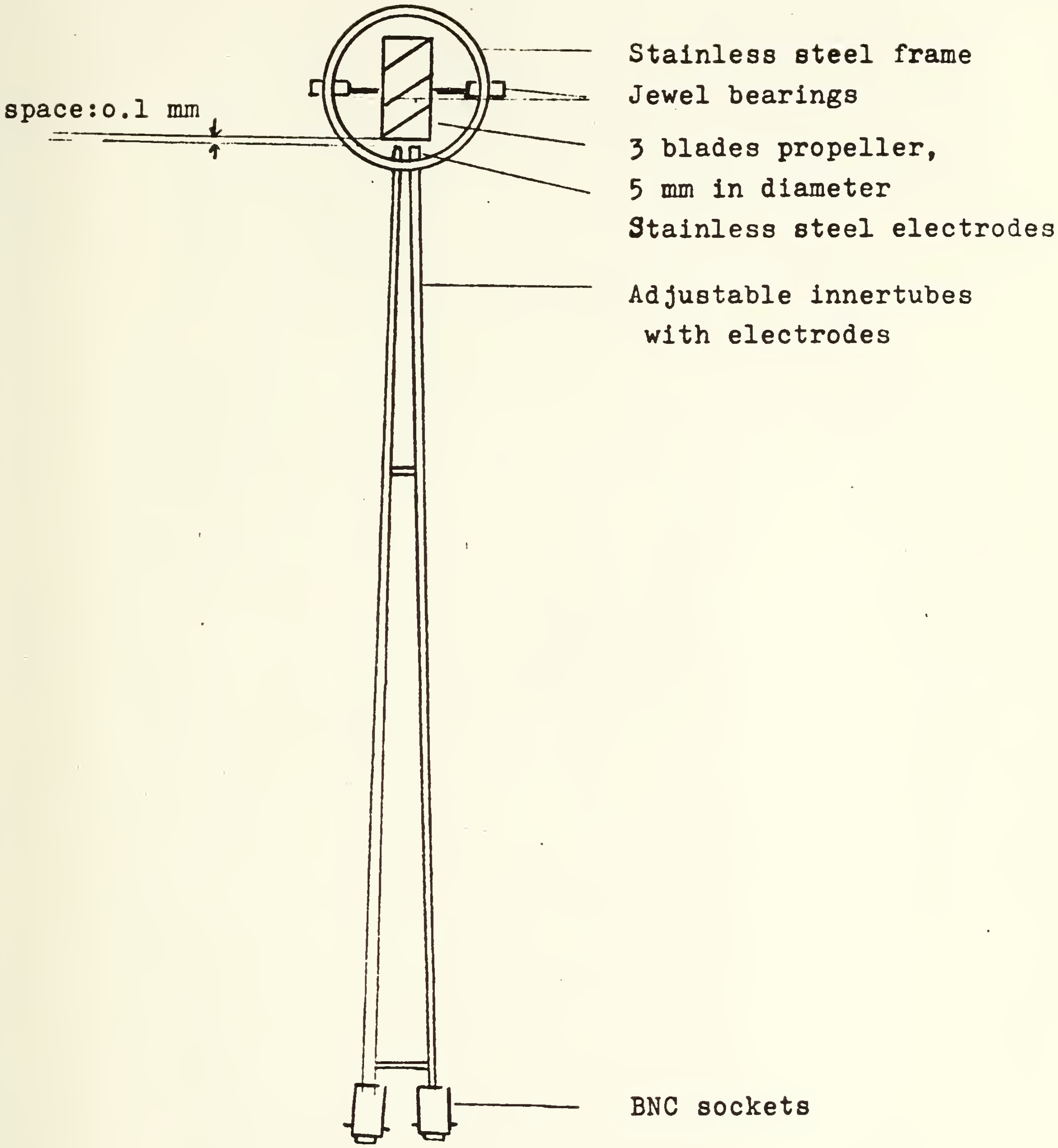


Figure 47. Hydrel Micropropeller Velocity Flowmeter

217546

Thesis
R26581 Reddish
c.1 Laboratory study of
plunging breaker wave
force distribution on
a slender pile.